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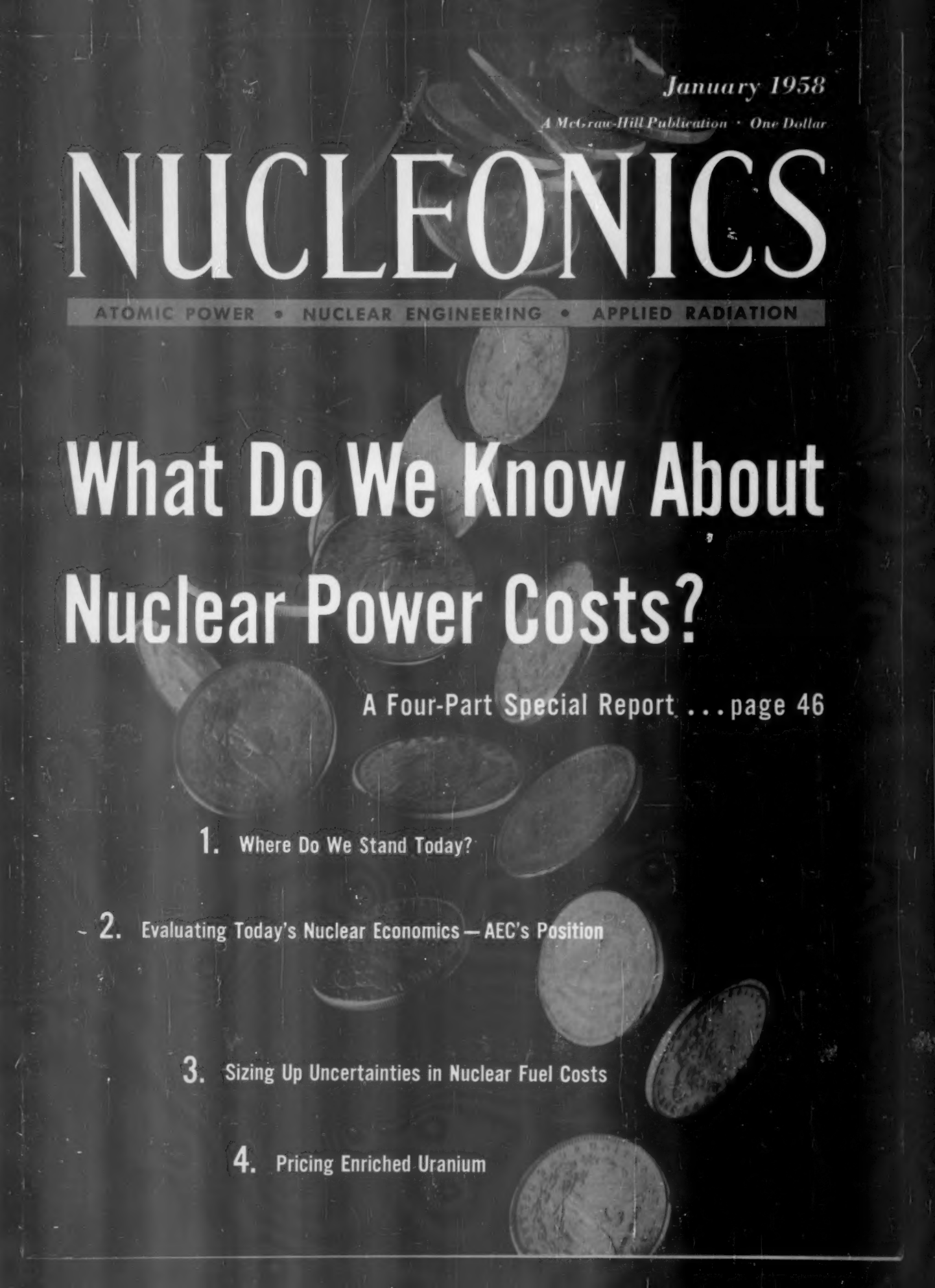
NUCLEONICS

ATOMIC POWER • NUCLEAR ENGINEERING • APPLIED RADIATION



What Do We Know About Nuclear Power Costs?

A Four-Part Special Report . . . page 46

1. Where Do We Stand Today?
2. Evaluating Today's Nuclear Economics — AEC's Position
3. Sizing Up Uncertainties in Nuclear Fuel Costs
4. Pricing Enriched Uranium

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VOLUME 16 NUMBER 1

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About NUCLEONICS

Thermonucleonics

In an article on controlled thermonuclear power that we published some time ago, we were unsuccessful in putting into the author's mouth a term that appealed to us as a name for the field—thermonucleonics. The gentleman in question said, politely, "If you want to coin the word, you take the responsibility for it!"

And so here we are doing just that. The column on p. 84 is a modest beginning in what we expect one day will be a rather important part of the editorial coverage of NUCLEONICS. It's a mechanism for keeping our subscribers posted on a continuing basis on technical and nontechnical developments.

The sparkplug (or perhaps we should say the spark discharge) behind the fue[illegible]n reporting that NUCLEONICS has done thus far—and that we will do in the future, including the new column—is physicist Dan Cooper, who finds that his soul requires that he supplement his managing editor responsibilities with "keeping in touch with good physics." And so, despite the inordinate obstacles imposed by secrecy, he has tried to plow through the woods of Project Sherwood and has, in fact, been able to keep tabs on some of the interesting happenings.

Making Sense of Cents

Some months ago we sensed that dollars and cents were the root of all evil in the nuclear business, that nuclear power costs were not doing what everyone wanted them to do—go down. Because the direction in which costs were going—up—resulted in misinterpretations of the health of the nuclear industry, we decided to try to do a little bit of "unconfusing" at the risk of making things worse by arranging for a series of articles on nuclear power costs. Then, suddenly, costs became the No. 1 story of the industry.

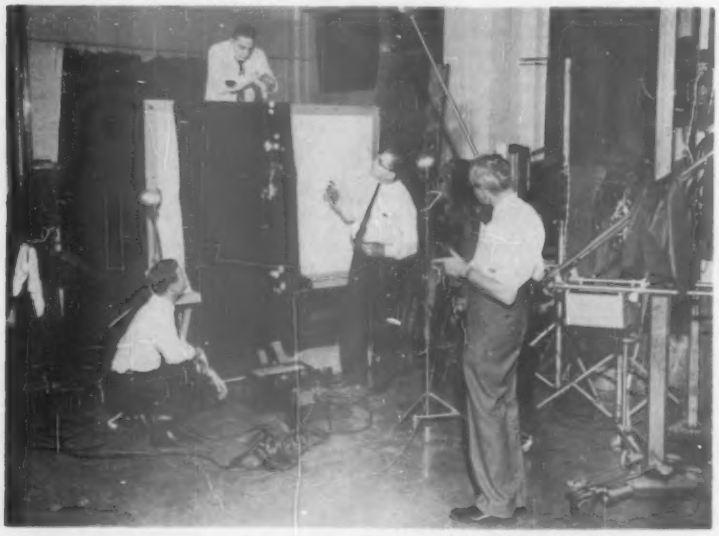
Thus, instead of waiting, we quickly decided to bring together in this issue (p. 46) a collection of material that fell very logically under the title, "Understanding Nuclear Power Costs."

The report on the American Nuclear Society symposium on fuel costs (p. 50) was born over a dinner table before the symposium. In the process of breaking bread with the speakers on the panel, our editors found that even though no one seemed to have any hard and fast answers on costs there was a worthwhile job to do in reporting the areas of agreement and confusion.

The Falling Dollar

While you can't tell a book by its cover we do feel that it's very important to package each issue of NUCLEONICS as interestingly as possible. Cover ideas originate in a conference that bring editors and art directors together to kick around the possible subjects. Actual implementation is the responsibility of the Art Department, and so it was that Art Director Harry Phillips and Assistant Art Director Roy Thompsen got involved with getting a picture of falling silver dollars for this month's cover. For picture of them in action, see figure on this page.

—The Editors



CATCHING THE NUCLEONIC DOLLAR. Hy Phillips (2nd from right) and Roy Thompsen (left) guard our artistic interests as this month's cover photograph is taken

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Industrial Heat Reactors

Reactor Foldout 4—
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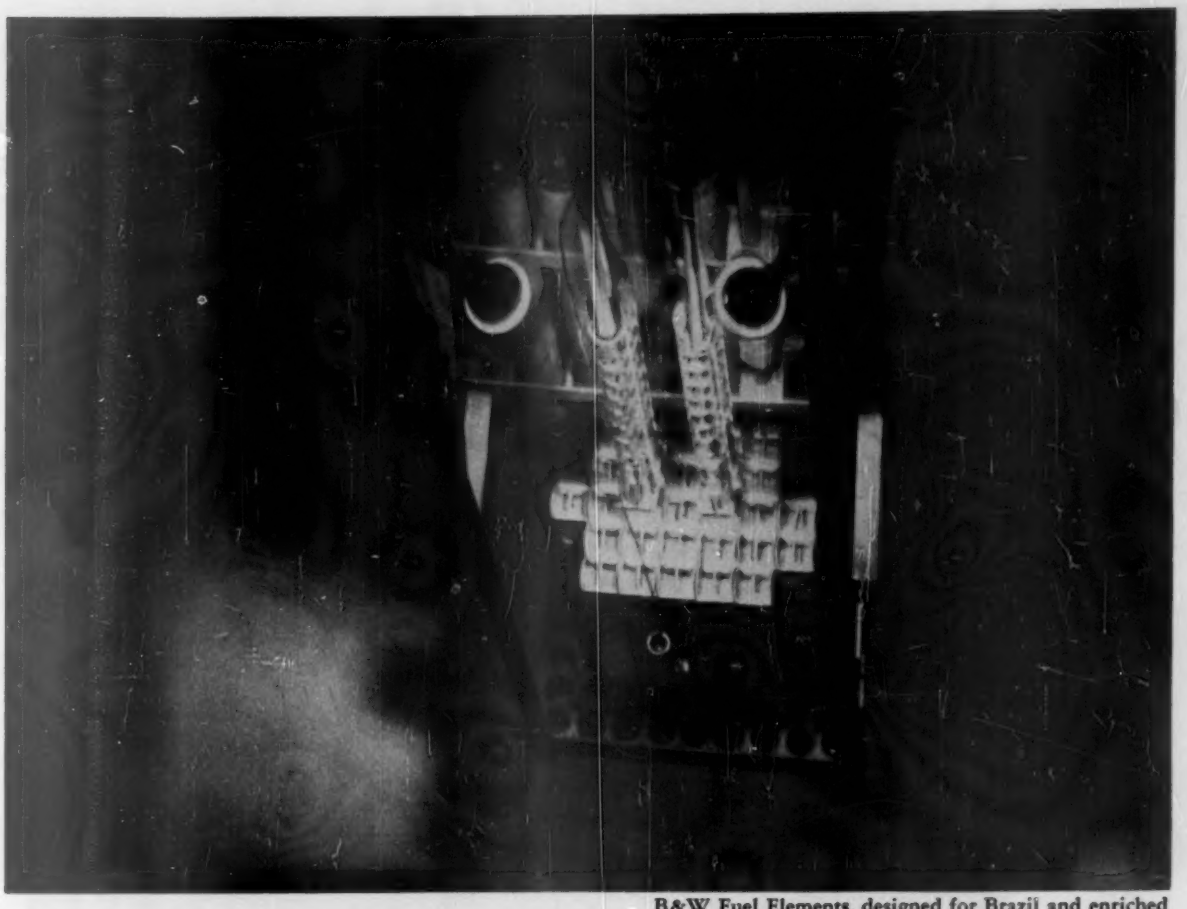
Gas-Cooling Thermodynamics

Later Months

Nuclear Patents

Special Report on Control Systems



B&W Fuel Elements, designed for Brazil and enriched to 20% U^{235}, shown during critical experiment.

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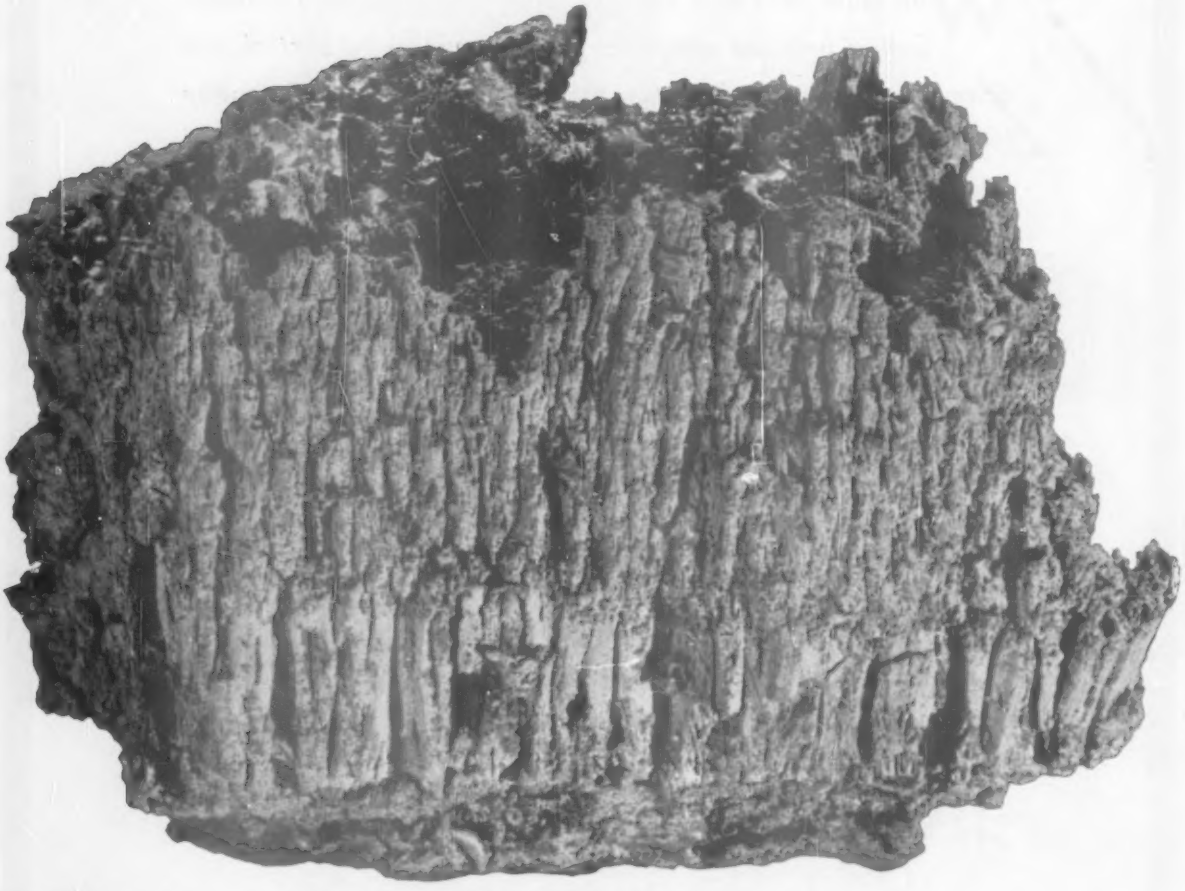

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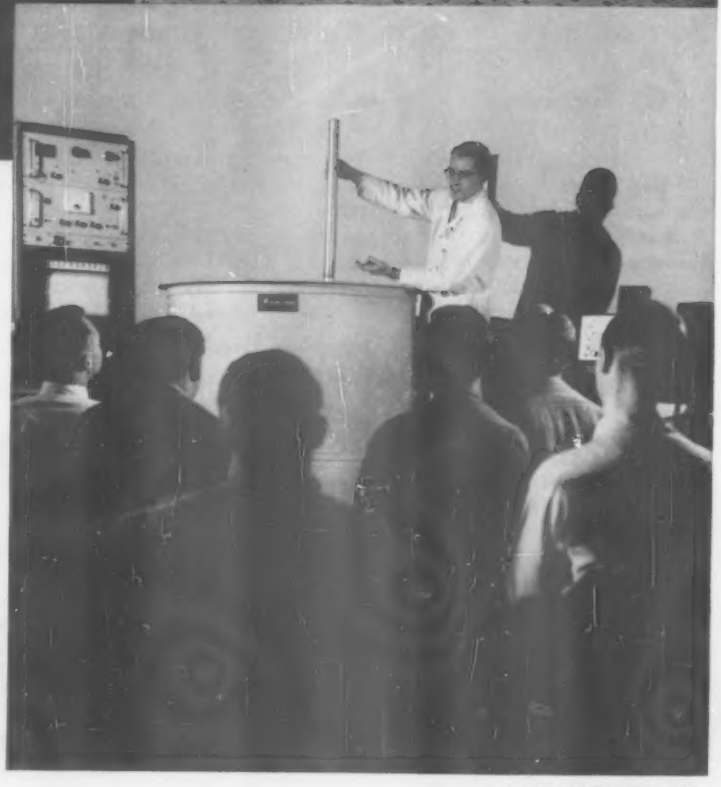
COLLEGES AND UNIVERSITIES COMPLETE NUCLEAR

A typical student nuclear engineering laboratory. At the left background is a well scintillation counter, scaler, and timer. On the same bench at the right is an automatic strip foil analyzer. An alpha survey meter and beta-gamma survey meter rest on top of the bench.

To the right, in front of an automatic gamma-ray recording spectrometer, a student surveys the area with a portable slow/fast neutron monitor. At the reactor, students make measurements within the uranium lattice with BF_3 counters.

At the right a student uses a scintillation detector in a manual sample changer. Beside him are two student counting systems. On the table in the foreground is an ion chamber type survey meter. These instruments, manufactured by Nuclear-Chicago, are all typical nuclear training tools which will contribute importantly to any nuclear engineering curriculum.



Instructor demonstrating insertion of aluminum tube into grid assembly in the Model 9000 Student Subcritical Reactor. 275 of these tubes, containing uranium fuel in the form of 1" x 8" slugs, are arranged in a hexagonal pattern in the reactor. Since the moderator is water, students actually can see the exact position of a detector or foil placed at any point within the uranium lattice.

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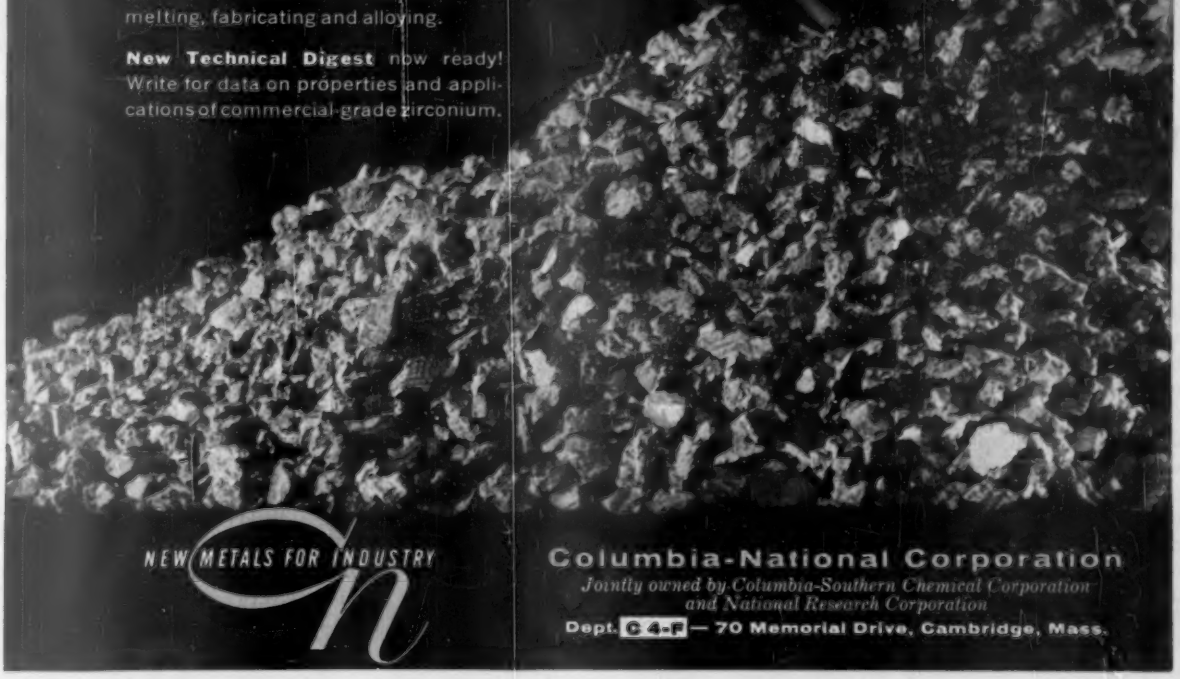

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CUSTOMER	REACTOR TYPE	POWER LEVEL
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Industrial Reactor Laboratories, Inc., Plainsboro, N. J.	Pool-Type	5000 KW
University of Buffalo, Buffalo, New York	Pool-Type	1000 KW
*Technical University of Munich, Munich, Germany	Pool-Type	1000 KW
*International Exhibition, Het Atoom, Amsterdam, Netherlands	Tank-Type, Demonstration	10 KW
Japanese Atomic Energy Research Institute, Tokai-Mura, Japan	Heavy Water, Tank-Type	10,000 KW
McMaster University, Hamilton, Ontario	Pool-Type	1000 KW
Greek Atomic Energy Commission, Aghia Paraskevi, Greece	Pool-Type	1000 KW
Union Carbide Corp., Sterling Forest, New York	Pool-Type	5000 KW
Societa Ricerche Impianti Nucleari, Milan, Italy	Pool-Type	1000 KW
AMF-GNE Educator, University of Florida, Gainesville, Florida	Training	10 KW
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How will a gear lube or a cermet—or for that matter, any material—stand up in a nuclear reactor? There is only one way to be certain. Expose samples to the intense neutron and gamma fields present in an operating reactor. Keep accurate environmental records, and, in a special facility, subject the samples to complete analysis.

NDA has advanced the art of in-pile testing to a science. It organizes the testing program, adapts capsules and environmental recording instruments for the in-pile tests, and, after irradiation, analyzes the samples, by now highly radioactive. This examination is carried out in a special radioactive materials facility of NDA-Pawling Laboratories. NDA has conducted a large number of complete in-pile tests, and its established procedures are quickly and economically adapted to new programs.

The need to know is imperative when a material is destined for use in a reactor. Firms interested in adding the growing reactor market to their customer list are invited to discuss a suitable in-pile testing program for their products.

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ROUNDUP of Key Developments in Atomic Energy

Budget Bureau Holdback of Funds Hurt Atomic Program

The men in the Atomic Energy Commission most responsible for our civilian nuclear program were recovering last month from the worst financial blow the Commission has had to absorb in its ten years of existence.

For six months, they were unable to get from the Bureau of the Budget any more than two-thirds of the operations money Congress had appropriated for the power reactor program. Moreover, they were forced during the same period to take a flat "no" on construction funds for several major reactor and research projects.

Measured in terms of progress on the peaceful atom, AEC's reactor people summed up, the effect was "extremely bad"; measured in terms of morale among AEC's scientists and operating personnel, the effect was "atrocious."

The struggle for the entire $350-million appropriated by Congress for the reactor development program was both silent and bitter, with several highly-regarded research-development workers threatening to throw in the towel because of lack of accomplishment.

The struggle began last summer when Congress cleared a $2.5-billion AEC budget for the current ('58) fiscal year (July 1, 1957 to June 30, 1958). It ended in mid-December when Budget Director Percival Brundage issued a general release on AEC's 1958 money.

The readily identifiable results: Some $40-million of the reactor appropriation of ~$350 million will not be spent this fiscal year (between 10 and 15%); the fast breeder reactor program has been set back 6–12 months; plans to expand or begin construction on a long list of research and development projects were simply discarded for the entire six-months' period; and the "ability to do a job" of many scientists in the program was seriously impaired.

There are three key terms which run through any discussion of this body-blow to the civilian program —economy, debt ceiling, and apportionment. The seed was planted during the nationwide ground-swell last year for economy in the federal government. Then, cutbacks on spending going beyond the cuts made by Congress became mandatory to prevent a puncture of the $275-billion debt ceiling. The incurring of any debt above that figure is illegal without the prior approval of Congress. A sharp reduction in the apportionment, by the Budget Bureau to the operating agencies, of appropriated funds was the logical way to hold spending down.

Hold That Line

On June 28, Brundage wrote to AEC Chairman Lewis L. Strauss—on behalf of President Eisenhower—directing AEC to hold the 1957 line on spending. A similar letter went to other agencies with non-defense activities. Among the guidelines in the letter to Strauss were these:

- Any departure from 1957 spending levels (about $2 billion) would

PWR at full power; HRE-2 critical

At 11:10 a.m. Dec. 23, the Shippingport PWR—the nation's first large-scale nuclear power plant—reached full power: 68 Mw(e). 8 Mw are required for the station's own service (5.5 to operate three main circulating pumps and 2.5 for other pumps, lighting and miscellaneous); 60 Mw were distributed to customers of Duquesne Light Co. in the Pittsburgh area (*details p. 86*). Meanwhile on Dec. 27, HRE-2 went critical at Oak Ridge (*see p. 23*).

2 utility groups pick up dropped Florida proposal

AEC has quietly rejected the third-round proposal of the Florida Nuclear Group to build a D_2O-moderated gas-cooled power reactor, but a new bid has been made for a more advanced reactor by two of the three original proponents jointly with another 14-member utility group.* Like its predecessor, the newly-proposed reactor would be D_2O-moderated and gas-cooled, but it would use slightly-enriched instead of natural uranium, pressure tubes instead of a large pressure vessel, would operate at higher temperatures, and have 50-Mw(e) capacity instead of 136 Mw. However it would serve as prototype for a 200-Mw plant. AEC rejected the original proposal because it asked AEC to bear all research-development costs with no ceiling. The new bid would have AEC and the utilities share research-development costs equally; the Florida West Coast group, on whose system the plant would be built, would finance the $25.9-million construction costs and would operate the plant. Completion date is set between June 1962 and June 1963 (although third-round rules require June 1962 completion). General Nuclear Engineering Corp. remains nuclear design agent and nuclear project engineer.

* Florida's Power Corp., Tampa Electric Co., and Florida Power & Light Co. were members of the Florida Nuclear Power Group that made the original proposal April 30, 1957; the first two have formed the Florida West Coast Nuclear Group. Joining it in the revised bid is the East Central Nuclear Group consisting of Appalachian Electric Power Co., Indiana & Michigan Electric Co., Ohio Power Co., Cleveland Electric Illuminating Co., Columbus & Southern Ohio Electric Co., Dayton Power & Light Co., Indianapolis Power & Light Co., Louisville Gas & Electric Co., Ohio Edison Co., Pennsylvania Power Co., Southern Indiana Gas & Electric Co., Monongahela Power Co., Potomac Edison Co., West Penn Power Co.

have to be justified to the Budget Bureau in writing, and all activities were to be subject to a "critical analysis" at both ends.

- For both construction and research-development, "the requests for apportionment . . . should reflect the postponement of a significant part of the obligations planned in the budget for 1958." So far as AEC's experience since July 1 is concerned, this pronouncement is the one that has hurt the most.
- Operating programs were to be reviewed after each of the first three quarters of the fiscal year for possible use of funds not spent during the previous quarter, or for possible reduction of the programs.

Furore in Congress

The Brundage letter caused a furore in Congress because it had the dual effect of (1) admitting that cuts were possible in a budget defended by the Administration as being already pared to the bone, and (2) making it clear that the Administration would attempt to operate at the fiscal '57 level regardless of the appropriations authorized by Congress in fiscal '58.

Brundage's "repudiation of the 1958 budget"—as it was to be called by the House Appropriations Committee—got AEC in trouble two weeks after it was written. Kenneth E. Fields, the general manager of the Commission, appeared before the House Appropriations group on the day news of the Brundage letter reached the newspapers. So he bore the brunt of committee abuse aimed at Brundage on how the Administration secretly "repudiated" the "highest peacetime budget of all time."

However, Committee Chairman Clarence Cannon raised no question about the legality of the executive's refusal to spend monies appropriated by the legislative branch. The legal question has been rendered moot by the lack of any enforcement power on the part of Congress. That body's only recourse is verbally to threaten the responsible administrative officials, who must eventually appear on Capitol Hill for more money. In 1949, President Truman successfully refused to spend appropriated funds to build up the Air Force; in 1956, Defense Secretary Charles Wilson did the same.

Effects in AEC

At any rate, the effect of the Administration policy as handed down by Brundage was to hold down AEC spending near the 1957 rate (weapons items excluded) until the general release issued by Brundage shortly before Christmas.

In fiscal 1957, AEC spent $54 million on its cooperative reactor program with industry and its own reactor experiment program. Between July 1 and mid-December this fiscal year its spending in the same areas was at an annual rate of about $60-million. It should have been, under normal apportionment procedures, at a rate slightly more than the $96-million appropriated for the current fiscal year.

More than $11-million for EBR II (for research, development and construction) was simply withheld. From the time this money was sought from Congress last spring until the program can get back on even keel early this year, nearly a full year has been lost.

Other major projects to feel the effects of delayed allotments were: the 12.5-Bev accelerator, where $1.5-million was belatedly cleared for design work in December; $3,550,000 to build a second "set-up" chamber for the cosmotron at Brookhaven National Laboratory (already operating around-the-clock, the cosmotron will be made available for use without the delay in cleaning up the preceding experiment); the merchant ship reactor—$7,978,000; $3,646,000 in particle accelerator funds; $401,000 for a Project Sherwood (thermonuclear) plant; almost $4,000,000 for hot cells at AEC laboratories; and the proposed fuels technology center at Argonne for research on plutonium, the ceramics of uranium, thorium and other materials, and the technology of solid and liquid fuels.

Also lab funds for important plutonium re-cycle work at Hanford; and $13-million for the long-lagging nuclear aircraft (ANP) project.

These comments came in mid-December from AEC officials:

"There has been a real slippage in all kinds of things (because of the apportionment situation). It certainly hasn't been very good for the (civilian) program, and it hasn't done the morale any good. The whole thing has been very bad—extremely bad.

"All kinds of things have not been started or have been delayed. We are now back to where we were several months ago if we had not had the hold-up, even though a lot of things have been done meantime.

"Several things would have been started or expanded several months ago. We are now in a position where we can pick up again."

JCAE Demands Account

The crisis brought angry action from the Joint Committee on Atomic Energy in Congress, which had so successfully rebuffed attempts within Congress to whittle down AEC's 1958 budget requests for the civilian program. Chairman Carl Durham, early in November, requested AEC to begin filing detailed reports on its apportionment experience vis-a-vis the Budget Bureau. He also tried to pin down Strauss on how much of the problem could be laid to the Commission's failure to ask for apportionment speed-up.

After an initial report last month, AEC was asked to supply the following information on a quarterly basis beginning this month:

1. Construction projects being deferred because Budget Bureau is withholding planned construction and acquisition funds;
2. Programs and sub-programs deferred because Budget is withholding operating funds;
3. Instances where the Commission has not requested appropriated

Cook Electric Co. growing in nuclear field

The statement in the December, 1957, issue of NUCLEONICS (p. 18) to the effect that the Cook Electric Co. had decided to drop out of the nuclear field was in error. The company has called to our attention the fact that it has a "continued lively interest . . . in the nuclear field" and that it is "growing fast in the industrial applications of nuclear energy, and in designing and building reactors for research and testing purposes."

The company has just announced the appointment of Harvard L. Hull as president of its Nucledyne Corp. subsidiary. Hull is a pioneer in the atomic energy field, having worked at Oak Ridge during the war and for nearly 10 years at Argonne National Laboratory after the war.

—The Editors

funds to be apportioned to it;

4. Instances where funds have been apportioned but are being withheld from use by the Commission itself.

The first report, filed by Strauss on December 13, gave these answers to the Joint Committee questionnaire for the period through November 30:

1. A list of 12–15 projects has been delayed by lack of funds; initial Budget Bureau refusal to allot funds has been followed by re-submission of the projects by AEC.

2. "It has not been necessary," the Strauss letter said, "to defer any programs or sub-programs" because of the apportionment policy.

3. AEC continuously appeals adverse Budget Bureau decisions on "projects of an urgent nature and has continued to submit apportionment requests as projects become urgent."

4. As to funds withheld by the Commission after allotment by the Budget Bureau, Strauss said that only minor amounts in both operating and construction categories have been held up—chiefly to maintain reserves.

Green Light from On High

The breeze which blew away most of AEC's current budget problems in December also dispersed a cloud hanging over the spending program proposed for fiscal '59. Although the fiscal '59 program—to be formally presented to Congress later this month—does not reflect a significant boost in non-military expenditures, it was dealt with harshly by Brundage when first presented to him in September.

He told AEC to cut back to the fiscal '58 level of appropriations. The routine appeal from this ruling, however, never came. Early in the week of December 9, the issue was settled by the President. Word came down from the White House to okay AEC's fiscal '59 program as originally tendered.

Perhaps more importantly, however, the new budget does not include a substantial boost in Federal spending on reactor development. Strauss gave a strong indication in his Santa Susana, Calif., speech that an expanded reactor program might be proposed (NU, Dec. '57, 19). His reactor aides and officials at the Budget Bureau have made it clear, however, that little expansion of the 1958 program is contemplated at this time.

Cranes hoist crane

Main section of circular crane 62 ft long weighing 27 tons and with lifting capacity of 12 tons is poised 48 ft above ground, about to be installed in reactor building. The bee-hive dome, to be 87 ft high when completed, will house Industrial Reactor Laboratories' 5-Mw pool reactor being built by AMF Atomics. Turner Construction Co. is building facility at Plainsboro, N. J.; it will be operated for IRL by Columbia Univ. To left of reactor building, labs are under construction

AEC splits off regulatory functions

AEC has reorganized its structure to separate regulatory from non-regulatory functions in its civilian program. The move, long urged by some in Congress, sees the Division of Civilian Application abolished. Its director, Harold L. Price, continues to head a new Division of Licensing and Regulation, which will handle all functions of regulating the private atomic industry. A newly-revived Office of Industrial Development (first set up in 1952) under Frank K. Pittman, former deputy director of Civilian Application, takes over non-regulatory tasks, with responsibility to encourage and assist growth of the private industry and to chart AEC policy to that end.

Westinghouse, AI in new ties in Germany

Two more foreign agreements have been concluded by U. S. firms girding for the foreign market (NU, Nov. '57, 17). Atomics International has set up a jointly-owned subsidiary firm with Demag AG of Duisburg, a leading West German firm in design and manufacture of heavy machinery and equipment. The new subsidiary, "Interatom," will design and fabricate research and power reactors and related products. It is the first international venture in Germany in reactor development and manufacture.

Westinghouse added another technical assistance agreement to its growing string, this one with Germany's vast Siemens organization, Europe's largest electrical manufacturer. The pact is along the same lines as earlier ones with A.C.E.C. in Belgium and Fiat in Italy (thus giving Westinghouse an in into three of the six Euratom nations); it provides for building and sale by Siemens of civilian reactors developed by Westinghouse, and supply to the U. S. firm of technology developed by Siemens.

Harmony Talks Start; JCAE Plans Hearings

Silence surrounded the first informal AEC-Joint Committee on Atomic Energy harmony meetings held late last month, with four Commissioners present while Chairman Strauss was away at the NATO meetings in Paris.

Just before they began, however, JCAE Chairman Durham released the reply Strauss had written to Durham's letter calling for such meetings (NU, Dec. '57, 18). The reply contained both adamant passages ("I regard our nuclear power policies and objectives as both clear and sound and our progress toward them satisfactory, and I have not noted in others the degree of uncertainty regarding them which you apparently have") and conciliatory ones ("I most certainly agree that the Commission and the Committee have a duty to work together to dispel any confusion which has arisen, for whatever reason and from whatever source. . . . I likewise feel that the fact of the passage of time and the consequent change in circumstances require both periodic review and a continual justification of objectives, policies and programs").

Before the "202 hearings" on the state of the atomic industry begin in mid-February, NUCLEONICS learned, JCAE's research-development subcommittee plans a hearing on basic research including the controlled fusion program and AEC accelerator projects (*see p. 27*). After the 202 sessions, JCAE will conduct a full-dress hearing into the waste-disposal problem and progress on it.

Other topics JCAE gave notice (in a Durham-to-Eisenhower letter) it intends to follow closely include support for the atoms-for-peace program through accelerated civilian reactor development, and the questions whether we are pushing nuclear airplane and rocket propulsion hard enough, and making enough A-subs and plutonium.

Exim Bank May Finance Nuclear Fuel Purchases

The Export-Import Bank of Washington "is prepared to look at suitable cases" of loans proposed for lease or purchase of nuclear fuel in connection with loans for construction of power plants abroad, NUCLEONICS learned (NU, Nov. '56, R3).

No More Fixed-Price Contracts For Reactors, GE Decides

General Electric is entering into no more fixed-price reactor contracts, President Ralph Cordiner announced last month. Escalator clauses allowing inclusion of unforeseen added costs will feature all future GE atomic pacts. GE has admitted to losing money on its $45-million fixed-price bid to build the Dresden station; it is silent on the amount, but guesses reach $15-million.

Brazil Sets '58 Goals; Setting Up Fuel Industry

Top priorities in Brazil's atomic energy program for next year are: 1. initiation of domestic fuel production; 2. expansion of domestic technical training; 3. expansion and stimulation—by bonuses, if possible—of prospecting and mining of uranium and thorium; 4. bilateral accords with other countries. These aims were disclosed by the chairman of Brazil's National Nuclear Energy Commission, Adm. Octacilio Cunha, in an exclusive NUCLEONICS interview.

In outlining this ambitious program, Admiral Cunha warned that several items of the agenda were awaiting congressional ratification, which might be slow in coming. However Brazil has taken a long step toward industrialization of her own atomic fuels by engaging a French company, Société Chimique de Produits de Terres Rares [Rare Earth Products Chemical Co.], to organize processing of local ore. This firm has already completed designs for a first-phase fuel production system, which will take zirconium ore bearing 0.5% uranium from Poços de Caldas, Minas Gerais, and channel it through two plants: the first will produce sodium uranate, the second will reduce it to uranium metal. One plant will be in mineral-rich Minas Gerais state, the other in industrial São Paulo state. The French firm will specify and advise on purchase of equipment—which is to be French-made—for the two plants, Admiral Cunha said. Some $5-million of French financing will come from the Bank of Indo-China and the Bank of Worms, both of which have done considerable industrial financing in Brazil. The last phase of the process—making fuel elements from uranium metal—has not yet been contracted for; studies are underway that might lead to use of

Hazards Unit Criticizes NACA Reactor Site

January 16 has been set for a public hearing in Washington on the application for a construction permit by the National Advisory Committee for Aeronautics to build a testing reactor. Jay A. Kyle of FCC who served also as AEC hearing examiner in the PRDC case (*see p. 27*) but merely presided, this time will render an initial decision.

Pursuant to last summer's change in the law, the report of the Advisory Committee on Reactor Safeguards on the application has meanwhile been published, and it reveals that ACRS is unhappy about NACA's choice of a site three miles south of Sandusky, Ohio, and only 59 miles from the heart of Cleveland.

The reactor is practically identical to the Materials Testing Reactor, but has flat- instead of curved-plate fuel elements and may reach 60 Mw(th) as compared with 40.

"The Committee is of the opinion that with the proposed container and at the selected site it is possible so to restrict the experimental program that the operation of the reactor will not result in appreciable hazard to the public," the report concedes. "However, the necessary restrictions may add materially to the cost of the program and may impose serious time delays. Further, some experiments which fall within the general type of experimental program proposed by NACA may not be permissible at this location. In view of the above, the Committee believes that the facility proposed would be more useful for the program proposed if it were located at a site less close to a center of population."

One member of ACRS, Abel Wolman, added a further statement: "In view of the prospect of future continuing debates as to the safety of conducting essential experiments at this site, I would recommend against the site on the information presently available. I believe that the applicant should be required to consider the availability of other sites at which operation of the reactor would be feasible and which would afford a higher degree of protection to the health and safety of the public. It is unrealistic to permit operation at this site if experiments of importance to the national defense are likely to have to be curtailed because of the site . . . "

British or European systems, the Admiral said.

Late last month the Nuclear Energy Commission was granted $2-million by congress for its operating needs—first of several grants hoped for. Also pending in Congress is a bill to authorize the Commission to pay premiums to mining and prospecting companies for bringing in uranium. At present the Commission is the only buyer of uranium and thorium in Brazil, and export of the two minerals is prohibited.

Several U. S. and European firms have been studying the possibility of installing plants to produce basic electronic equipment and instruments for Brazil's new atomic industry, Admiral Cunha said, adding that there were many opportunities for foreign firms to supply equipment for the fuel processing system now being undertaken. Brazil also sorely needs many more geologists and other technicians to expand prospecting, he added.

Regarding nuclear power, the Admiral said the only concrete plan before his Commission was the American & Foreign Power Co. project for a 10-Mw boiling water reactor. Meanwhile reports from São Paulo state are that Janio Quadros, the state governor, and his experts are studying two reactor proposals: one for a Martin Co. pressurized water, enriched-U plant (NU, June '57, 17); the other for a British Calder-type natural-U station.

Norway Installing Halden Components

Work on Norway's boiling water reactor at Halden, south of Oslo, has now reached the installation stage. The experimental unit, with a capacity of 20 Mw(th), will deliver steam at 482° F and 588 psi; but its experimental function is considered more important for the knowledge it will yield. One of the Norwegians' main objects at Halden will be to develop a reactor type suitable for ship propulsion.

The reactor core will be contained in a stainless-steel-lined, mild steel pressure vessel of 8 ft 10 in internal diameter and 13 ft 2 in cylindrical internal height. The tank itself is of conventional shape with a curved bottom and a flange ring at the top. The lid, however, is highly unconventional for the pressure and diameter in question. Owing to the necessity of having all fuel elements similar, conventional designs have been replaced by a lid consisting of a 2 ft 4 in flat steel slab, bolted directly to the flange ring. Some 26 holes for steam outlet and condensate return pipes and 335 holes for fuel elements and control rods have been bored in the top lid. The tank and lid, which is machined and assembled by A/S Kværner Brug, Oslo, is ready for pressure-testing. The lid will probably be nickel-plated prior to installation to prevent its corrosion.

The cadium control units, made at the Chr. Michelsens Institute, Bergen, are ready for installation. All units are exactly similar in design, and can be used either as scram, shim or fine control rods, depending upon the motor drives and electrical system to which the individual rod is connected.

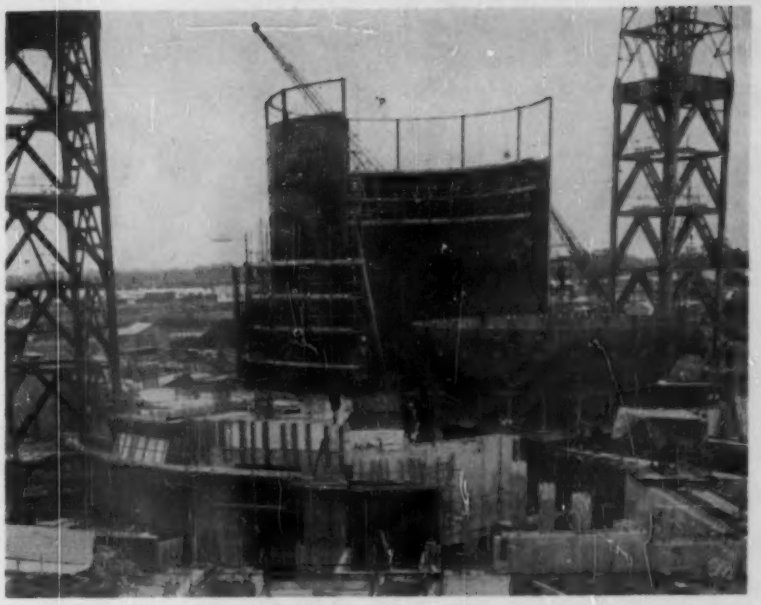
The heat exchanger system, made by A/S Thunes Værksted, Oslo, is being completed.

In the reactor hall, the installation of the light-water circuit is well under way. The steam drum is the biggest component installed up to now. The heavy-water storage tank and a number of pumps and valves have been installed.

In the control room the installations are being completed. The main control panel is built around a graphic panel. This is an almost complete flow diagram with valve and pump annunciators and indicators for the most important process variables.

Most of the main components, such as the reactor tank, the heat exchangers and subcooling system have yet to be installed. After installation the whole reactor system will be leak- and pressure-tested.

The reactor is expected to go critical in early summer of 1958. The Organization for European Economic Cooperation, which has a study group working up a proposal for a joint European experimental boiling water reactor, has been interested in the Halden project for some time and is said to be considering suggesting that OEEC take over operation of the Halden reactor for a few years. Norway, interested in success of the OEEC idea of European economic cooperation, is reported receptive to such a suggestion.



Putting the bottom in

One of the odder railway journeys took place recently at site of Britain's Berkeley nuclear station when 200-ton bottom dome of steel pressure vessel for No. 1 Reactor was brought to its foundation, from its temporary welding chamber where it had been under construction for five months. Long lead time required its prefabrication off to one side while foundation was being prepared; this will not be necessary for No. 2 Reactor at Berkeley which will be assembled on completed foundations. Each vessel will be 80 ft high, 50 ft dia; they are world's largest to be welded from 3-in. plate—2½ times larger than Calder Hall vessels of 2-in. plate. Three production lines have been set up on site to turn out 16 boilers, eight per reactor

'Long Beach' Keel Laid; Other A-Ships Advance

The U. S.'s first nuclear surface ship became tangible last month when the keel of the USS *Long Beach* was laid at Bethlehem Steel's Fore River shipyard, Quincy, Mass. An eight-ton, 60-ft keel section was lowered into place in a new and enormous (world's largest) shipbuilding basin, in the presence of notables, to give a ceremonial start to construction of the 14,000-ton displacement guided-missile cruiser. To be 721 ft long, 73 ft in beam and to cost about $100,000,000, *Long Beach* will have "high speed" and "virtually unlimited cruising radius" when she is delivered in 1961. Westinghouse is building her twin reactors, and has received a $2-million contract for six turbine-generators, each rated at 2,500 kw and largest ever designed for use aboard a naval vessel. Condensing apparatus, voltage regulators and other equipment will also be supplied by Westinghouse. Bethlehem is designing the lead-bonded-on-steel reactor shielding, as well as the propulsion machinery.

• Meanwhile a $20.9-million contract for construction of the second U. S. nuclear surface ship, the N. S. *Savannah*, was signed by representatives of the government and New York Shipbuilding Corp. of Camden, N. J. (NU, Dec. '57, 24). Keel-laying was set for May 22.

• And Rep. Thor Tollefson of Washington, ranking Republican on the House Merchant Marine committee, said he would introduce a bill this year for construction of an American nuclear icebreaker to meet present and future U. S. needs in the polar areas.

• *Skate*, the Navy's third nuclear sub, was commissioned Dec. 23.

• General Electric has completed a reactor core mockup for the first nuclear destroyer. The unit, at Knolls Atomic Power Laboratory, is called PMA for Plastic Mockup Assembly, being moderated by plastic to simulate pressurized water. It is being used to determine optimum fuel pattern for the D1G (destroyer) reactor; two reactors will be used aboard the vessel. GE is working in collaboration with Bethlehem Steel, which has a design contract on a nuclear power plant for a destroyer for the Navy, and has succeeded, it says, in overcoming the formidable design problems of integrating a nuclear propulsion plant into a ship the size of a destroyer.

The Bethlehem end of this job, like that of designing *Long Beach*, falls to the nuclear power branch of the Bethlehem shipyards' Central Technical Department, which is responsible for the tailoring and arrangement of the reactor to the ship. They, in collaboration with Westinghouse and the Navy, establish the type, size and arrangement of machinery and machinery spaces; design the shielding; and have subcontracts with Westinghouse relating to reactor design under which the Bethlehem groups aid in developing the plant to make it suitable for a naval vessel as to size, performance and control, and shield design. The nuclear power branch at Bethlehem now has 150 men assigned to the cruiser project, 60% of them professional engineers, and over half of those in turn having special nuclear engineering training; about 75 are working on the destroyer project. In addition there will be about 300 draftsmen on the Fore River shipyard staff preparing the final working blueprints for *Long Beach*, plus 1,000 production workers.

The nuclear power branch, now in its fourth year, has made studies on nuclear tankers. Its research and development laboratory at Fore River has carried out some shielding research on scattering, is working on an improved method of bonding lead on steel; and has developed a rig, which it is now testing, that will make possible automatic welding of stainless steel pipe up to 18 in. dia, 1¼ in. wall thickness.

Lenin launched
On Dec. 5 in the rain in Leningrad, the Russians launched their pioneer nuclear surface ship, the icebreaker 'Lenin.' Her port of registry is Murmansk. Box-like structure under stern is evidently a pontoon-float launching cradle. Compare photo NU, Aug '57, 18. The Russians announced they will lay the keel for a sistership at once

OEEC Forms Atom Unit; Euratom All Ratified

The 17 West European nations of the Organization for European Economic Cooperation have formed a European Nuclear Energy Agency to promote cooperative peaceful atomic projects. In this long-planned body (NU, Aug. '56, R11; May '57, 20), the six Euratom nations are joined by Britain, Ireland, Norway, Denmark, Sweden, Iceland, Portugal, Switzerland, Austria, Greece and Turkey. Sponsors insist there is no contradiction between the new ENEA and Euratom; the former involves in pooling, but rather planning of projects which members may join or not as they wish. ENEA will seek to spread the cost burden by joint participation, and to avoid duplication of effort.

A first fruit was establishment by 12 OEEC members of Eurochemie Co., which will build and operate a $12-million plutonium-separation plant at Mol, Belgium, to be completed in 1961. Eurochemie is capitalized at $20-million.

Meanwhile the Dutch Parliament supplied the sixth and last ratification needed for the Euratom treaty, which came into force Jan. 1.

Uranium Men Study AEC Leveling-Off Order

Worried uranium producers, concerned over the meaning of AEC's "no more expansion" statement in October, gathered at a two-day meeting in Denver last month to determine where they stood. In spite of AEC efforts to mollify them, they appeared to be still confused by AEC's position: to encourage continued exploration, while shutting off further purchases.

Uranium has grown at a breathtaking pace: in 12 years the industry has flashed from virtually nothing to the second-largest dollar-value commodity in the U. S. (second only to copper).

With uranium deliveries to AEC appearing "adequate for military and power requirements as projected on an annual basis for the next few years," Jesse C. Johnson, director of AEC's raw materials division, told the Atomic Industrial Forum in October that "it no longer is in the interest of the government to expand production of uranium concentrate." AEC will attempt to limit production to the level to be reached as a result of existing commitments, and new mill contracts will be given only for areas having no present milling capacity. No new commitments have been made for foreign buying for some years.

This was the gloomy background for the Uranium Institute of America meeting last month. At least one major producer was satisfied: "As Johnson makes clear, there is not 'too much uranium,'" said Donald H. McLaughlin, president of Homestake Mining Co. "We don't know how well off we are. What other industry, besides gold, has a sure market for the next nine years? Exploration . . . must be appraised as a business risk involving market uncertainties; I'm happy to do it." But others were more skeptical about spending their money to turn up a product they might not be able to sell to the only buyer. AEC appeared to some to be in a position where it could gamble: it must contract for five years' output to get a new mill built now, but a mill can be built in 1½ years.

Nuclear economists attending the session pictured a glum future for uranium. Stuart McLain estimated a total of only 15,000–30,000 tons of uranium needed for nuclear power stations over the period 1958–67.

There is on uranium stockpile, other than weapons, "except what's in the pipeline," John T. Sherman of AEC revealed. "We do not have a stockpile of yellow cake, green salt, hexafluoride or metal; ore stockpile contains about 1.5-million tons."

NUCLEONICS Surveys Opinion On U. S. Reactor Policies

In January 1957, just prior to the annual "state of the industry" hearings of the Joint Committee on Atomic Energy, NUCLEONICS published the results of an 11-nation survey on matters related to world leadership in atomic energy. Now, because once again development of U. S. atomic power policies is of urgent concern to the industry and because Congress is about to review these policies, NUCLEONICS is conducting another survey, aimed at shedding light on thinking in the U. S. and abroad on current nuclear problems.

It is designed to pinpoint what key people in the nuclear field think about objectives, size, scope and timing of the U. S. atomic program. Since early December, NUCLEONICS correspondents have been interviewing leaders in the U. S. and 11 foreign countries that are potential markets for U. S. atomic products. Others are being queried by mail. Results of the survey will be published next month.

The Month in the Labs

Argonne

Treat (Transient Reactor Test)—Architect-engineer design work completed, specifications approved; bids to be opened Jan. 28 (*more details p. 26*).

Experimental Boiling Water Reactor—On Dec. 2 reactor was run up to 46.6 Mw(th), Dec. 23–24 to 50 Mw(th) and held for several hours (design power is 20 Mw(th)). No oscillatory tendencies appeared, and indications are that the reactor is now limited in steady operation more by the amount of reactivity built into the controls than by any question of stability. Electric generation was limited by turbine size to 6,250 Kw (1,250 over design power); rest of steam was bypassed to condenser. Argonne engineers believe maximum stable power of which EBWR is capable is still higher, and that with forced cooling it could produce 100 Mw(th), 25 Mw(e). This would significantly reduce power cost, as previously pointed out (NU, Nov. '57, 21).

Brookhaven

Medical Reactor—Outside of containment vessel being welded up; part of shielding, and the linings for shutters, are in place.

Oak Ridge

Homogeneous Reactor Test—Went critical at 6 p.m. Dec. 27; ran for 1–2 hrs at 28° C—1/10 of design temperature. Low-power preliminary tests now under way to establish satisfactory operation of all parts and to determine temperature coefficient before full power, 5 Mw(th), is reached.

National Reactor Testing Station, Idaho

Argonne Low Power Reactor—Pressure vessel has been installed in containment tank; major work up to operating-floor level being completed.

Engineering Test Reactor—Tests during the past two months have considerably improved outlook for solution of ETR's fuel element problems reported two months ago (*see p. 102*), NUCLEONICS learned. Results were "pretty favorable" on all tests that could be applied at room temperature to elements modified by "not very radical changes" in design. Two more full core-loads have been ordered, one having element side plates slotted, one with meat plates cold-rolled to improve structural strength; such elements stood up in tests to 140% of design coolant flow. After operating only at very low power since going critical last Sept. 19, ETR reached 30 Mw late last month and has approval to go to 90; design power is 175 Mw. Meanwhile it is already at work, doing some capsule irradiations.

SPERT-1—Static measurements on the B core were completed, another series of transients are under way.

SPERT-3—Pressure vessel arrived, was installed; entire facility now about 45% complete.

Domestic-Built Power Reactors Are West German Goal; Four Design Groups Working, 4 Utility Groups Formed

BONN

West Germany, on her way to catching up with the world leaders' level of atomic development, is pushing a program aimed at perfecting home-grown industrial power reactors.

In the field of research reactors, the Munich reactor has gone critical, the Frankfurt reactor is about to go critical, the Berlin reactor has arrived and is being assembled, the Karlsruhe and Jülich reactors are under construction, and planning for the Hamburg reactor is completed.

The next step, a blueprint calling for four-to-five power reactors totaling 500 Mw(e), has now been approved by the German Atomic Commission. Under this program, the following projects are to be developed and completed by 1965 by German private industrial firms now already working on them:

1. An advanced, gas-cooled, graphite-moderated reactor fueled with natural uranium—Deutsche Babcock & Wilcox;

2. A heavy water moderated and cooled reactor fueled with natural uranium—AEG (Allgemeine Elektrizitäts Gesellschaft);

3. A light water moderated and cooled reactor with slightly enriched uranium fuel—Siemens-Schuckert;

4. An advanced high-temperature reactor using gas cooling and enriched uranium fuel—Brown Boveri in cooperation with Krupp.

Each of these reactors is to have a capacity of about 100 Mw(e); each will be undertaken by a group of electric power utilities. Unlike the research reactors which—with the single exception of the Karlsruhe unit—are all ordered from American or British manufacturers, the power reactors will be fabricated and supplied primarily by German companies. This seems certain even though only one order has been placed so far.

Utility Groups

That one firm order was given by AVR, a group of nine West and North German public power companies headed by the Düsseldorf Power Co., to Brown Boveri Co. of Mannheim (German subsidiary of Brown Boveri of Switzerland) which, in cooperation with Krupp, is developing a high-temperature reactor using enriched uranium in ceramic fuel elements and gas cooling (NU, June '57, 23). The present development contract is to be followed in about two years' time by an actual construction order.

Two groups are considering the Siemens and the AEG reactor designs. One is a Bavarian group, Gesellschraft für die Entwicklung der Atomkraft in Bayern m.b.H. (Company for Development of Atomic Power in Bavaria), consisting of the power-supply companies Bayernwerk, Innwerk and Isar-Amper Werke plus Farbwerke Höchst and the Bavarian government. The other is a group of Westphalian and Lower Saxonian power utilities, Studiengesellschaft für Kernkraftwerke (Study Company for Nuclear Power Plants). Which group will buy which reactor type has not yet been decided.

A fourth group in Baden-Württemberg state, headed by the public power supply firm Badenwerk, is thinking in terms of a Babcock & Wilcox reactor of the Calder type.

While all these groups will probably order reactors domestically, the largest German power company, RWE (Rheinisch-Westfälisches Elektrizitätswerk) in Düsseldorf, is negotiating with General Electric and with several British firms on a 10–15-Mw(e) pilot plant at a cost of about $7-million. The deal originally concluded with the AMF-Mitchell Engineering group was cancelled (NU, Nov. '57, 19), primarily because of difficulties over AMF's Elk River reactor project. RWE would also be willing to order a 200-Mw(e) reactor at a cost of $75–85-million provided it would produce electricity at competitive cost. At the moment, however, operating costs of all reactors on the market are still about 50% above the price of coal-produced electricity. By the time the power plant project materializes, RWE too may switch to domestically-built reactors.

The Euratom Target

In comparison with the 6,000 Mw called for in Germany under the Euratom 15,000-Mw program, the 500 Mw presently scheduled in Germany seems small. But aside from the fact that the energy gap expected by the Euratom "wise men" in 1967 is subject to discussion and may well be an overestimation, the German government has no means of forcing industry to undertake costly projects under Germany's free market system, and the companies have neither enough capital nor authority from their shareholders to get too deeply involved in costly power reactors.

The program as it now stands will cost $520–570-million. It includes the establishment of facilities costing about $250-million for radiation protection, fuel production and for the processing of fission products; and $120-million for four years' research.

The reactors will require 400 tons of natural uranium, 40 tons of slightly enriched (1–1.5%) and 300 kg of 20% enriched uranium, 2,000 tons of graphite, 150 tons of heavy water, 50–60 tons of zirconium, about 50 tons of thorium. The enriched uranium is to be supplied by the U. S., later through Euratom. However as regards natural uranium, it is generally felt here that Germany should not entirely rely on imports but should step up domestic production even though the price for German concentrate may in the beginning be above the world market level. Furthermore, an expansion of heavy-water production over the present annual capacity at Farbwerke Höchst of 6 tons is planned, and fuel production facilities will require additional investments.

The reactors themselves will cost approximately $250-million, to be shouldered jointly by industry and government. The power companies will finance one-third of the cost of project development, which alone equals the cost of a conventional power plant, and one-third of the construction order. The government will contribute the other two-thirds of development costs, and one-third of construction costs covering expenses for radiation protection and safety installations. The last third of construction costs will be met through tax exemptions, governmental loans and other indirect subsidies.

All this planning has been done in the absence of a federal atomic law which, however, is expected to be passed before the end of this year, long before any German project for a power reactor can crystallize. So-called pre-projects would be completed within a year after the order is placed. Another two years will be required for development, after which construction of the actual power station—another three years—could begin.

World News

Nuclear Plants Bruited for Korea, Hawaii

The South Korean government's idea to build a 15–45-Mw(e) nuclear power plant was endorsed by William Warne, American chief of the U. N. economic aid mission. The country has no fossil fuel. Seoul hopes to get financial aid from the U. S. development loan fund, World Bank or Export-Import Bank. In Hawaii, Hawaiian Electric Co. has taken steps to acquire a 485-acre site 20 mi from Honolulu for a power station; the site—Kahe Valley, where the mountains form a natural horseshoe facing the sea—is suitable for a nuclear plant, and economic feasibility studies on a nuclear station are now being made. Hawaii also lacks fossil fuels; Westinghouse president Gwilym A. Price recently commented that "it seems highly likely nuclear plants will be economically feasible in Hawaii sooner than in any other part of America."

Japan: Isotope Production, Reactor Hesitation

Trial production of radioisotopes has begun with Japan's first research reactor, operating since November at Tokai village N of Tokyo. Sodium-24, for use as a tracer in medical experiments, is the main product. However the year-long indecision on buying a British Calder-type reactor is not yet over; another survey mission is going to England, after nearly having its trip postponed several months because of the Japanese AEC's doubts about the ability of the Calder-type to withstand earthquakes. And a group of nuclear physicists has asked the JAEC to postpone a decision until after the second Geneva Conference in September.

Austria Completes First Reactor Specs

Austrian firms have been given the specifications for the country's first research reactor, a 5-Mw(th) pool, with 10^{13} neutron flux. The $500,000 unit, with a 15–24-month delivery time, will have two thermal columns and one or two 8-in. and four to six smaller beam tubes. Four sites, all within 50 mi of Vienna, are under consideration. The second reactor planned, for 1960–61 completion, is a materials testing unit; the third for 1964–67 completion, will be Austria's first power reactor. Independently, the U. S. has offered (subject to Congress' approval) a research reactor to the International Atomic Energy Agency, whose seat is in Vienna.

German Lab Site Moved Again

For the second time, the West German state of North Rhine–Westphalia has changed the site for its $20-million nuclear research center (NU, June '57, 27), moving it to the Stetternich Forest near Jülich. Preparatory construction work has started. The earlier site near Düren was abandoned because it would have been on top of 480-million tons of brown coal and hindered its mining. Two British research reactors have been ordered for the center.

East Germany: Power, Research Reactor Milestones

Construction of East Germany's first power reactor has begun north of Berlin (NU, Feb. '57, R9), according to East German sources. The 70-Mw(e) reactor, of unstated type, is being furnished largely by Russia; a two-mile exclusion area has been established. Meanwhile East Germany's first research reactor went into operation at Rossendorf near Dresden. The 2-Mw water reactor is identical with those supplied by Russia to Rumania (NU, Sept. '57, 24) and Czechoslovakia (NU, Nov. '57, 26).

U. N. Names Perrin, Fixes Radiation Session

Francis Perrin, French High Commissioner for Atomic Energy, was selected as president of the second Geneva conference in September, by the U. N.'s Advisory Committee on Atomic Energy. Homi J. Bhabha of India was president of the 1955 conference. The U. N. also set Jan. 27 as starting date of the fourth session of the 15-nation Scientific Committee on Effects of Atomic Radiation (NU, Dec. '56, R6). The session will discuss the first draft of its comprehensive report to the General Assembly on radiation effects, based on 130 reports from 27 nations and U. N. bodies received to date.

Uranium Shipped to Argentina, Spain

$110,000 worth of uranium for Argentina and $112,000 worth for Spain cleared New York's Idlewild Airport last month. 36 kg (80 lb) of 20%-enriched U_3O_8 were destined for an Argonaut being built in Buenos Aires by the Argentine National Commission for Atomic Energy; 30 rods containing 20 kg of 20%-enriched metal were bound for the 3-Mw pool that General Electric is building at Moncloa near Madrid for Spain's Junta de Energia Nuclear.

French Firms Found Fuel Company

St. Gobain, one of France's leading chemical firms, and Forges et Ateliers du Creusot, her biggest metallurgical and construction company, have jointly set up a new firm for research and development in nuclear fuels: Centre de Recherches pour Combustibles Atomiques (CERCA), with a capitalization of 250-million frs ($600,000). Both founders have long been active in the French nuclear program.

Reds Deliver Reactor for Egypt

"All the parts of the atomic reactor imported from the Soviet Union by Egypt" have now been delivered and will be assembled by Egyptian engineers under supervision of Russian technicians, reports the Cairo semi-official Middle East News Agency. The reactor building is not yet completed, but the adjoining nuclear research laboratory building—also to be outfitted by Russia—is finished. Ibrahim Hilmi Abdul Rahman, secretary of the Egyptian AEC, said the research reactor would be in operation by the end of 1958, and that EAEC had decided to build a nuclear power plant between 1962 and 1967. He said 150 Egyptians are now being trained as nuclear experts.

Fairey Joins Atomic Power Group

Fairey Aviation Co. Ltd., one of Britain's largest aircraft builders, has joined Atomic Power Constructions Ltd., the fifth U. K. consortium (NU, Feb. '57, R11).

Rum Jungle U-Figures Out

First figures on operations at Rum Jungle, Australia's big uranium center, show a steep upward curve. Uranium and uranium-copper ore treated at the government-owned plant rose from 50,720 tons in fiscal 1956 to 71,628 in fiscal 1957; uranium content rose from 8.4 to 9.1 lb/ton; production of uranium oxide went from 333,546 to 541,652 lb concentrate. The last figure exceeds both the estimate and rated capacity of the plant.

Reactor News

EBR-1 CRITICAL AGAIN

The Mark III core in AEC's Experimental Breeder 1 achieved criticality Nov. 11, 1957, and is undergoing preliminary tests prior to operating at power again. It was the first time the reactor had operated since the meltdown incident of Nov. 29, 1955 (NU, June '56, 35; Jan. '57, 84). On completion of tests, the reactor will be used to investigate "the effects of mechanical, hydraulic, thermal and nuclear variants on the stability of fast reactors." The new core, product of two years of research and design work, is expected to perform with greater stability than the first two; mechanical motion of the fuel pins is rigidly controlled to prevent their bowing, believed to have been a prime cause of the meltdown. The 9-ft 5-in. core will operate at 1,400 kw(th), 200 kw(e).

PAR FILES FOR THIRD-ROUND AID

A proposal for AEC reactor construction aid, the fourth under the third round of the power demonstration program, has been filed on behalf of the PAR project by Pennsylvania Power & Light Co. and Westinghouse. PAR —the Pennsylvania Advanced Reactor, a large-scale homogeneous type—was first announced in July 1955, and has been under active development since August 1955. $5.5-million of private capital has been spent to date by the two firms. Their joint proposal asks, first, $7.3-million AEC financial support for further research and development during 1958–59, and second, promises a decision in December 1959 to begin actual construction of a plant to be completed by end of 1963, or termination of the project if the results of the next two years' research do not warrant building the nuclear station. If the plant is to be built, AEC aid up to $18-million during construction and the first five years of operation is sought, as well as waiver of uranium and heavy-water use charges. If the project is terminated after two years, the firms undertake to repay AEC for research aid during 1958–59. Although all known PAR reference designs to date had been for a 150-Mw(e) plant, the third-round proposal refers to a plant with a generating capacity of 70–150 Mw(e).

Back in June AEC extended the minimum completion date for third-round plants using fluid fuel reactors from June 30, 1962, to "at least" June 30, 1963, in a move then interpreted as applying principally to PAR; but P. P. & L. officials at the time told NUCLEONICS that the extension did not apply to them as the new date was still too restrictive (NU, July '57, 25).

LEAKS HOLD UP DANISH REACTOR

A 3–6-month delay in completion of Denmark's second, tank-type research reactor has been caused by leaks in the tank. Thirty holes were found during testing of the aluminum vessel, already mounted at the Risø nuclear center. Foster Wheeler Corp., builder of the reactor and fabricator of the tank, has sent John Cartinhour, nuclear department manager, to Risø to investigate. Repairs are said to require $40,000; Danish firms have offered to do the rewelding.

ALASKA REACTOR FINALLY SET

The long-projected package power reactor for Alaska (NU, Aug. '56, R9; Apr. '57, 19; July, 25) has been authorized by the Army. Modeled on the APPR at Ft. Belvoir, APPR-1b will be built at Ft. Greely, 60 mi S of Fairbanks on the Alaskan Highway. It will produce 42-million Btu and 1.7 Mw(e) for Ft. Greely. Congress has authorized $6,675,000 for the project.

LPTR STARTED UP

The Livermore Pool-Type Reactor went critical Dec. 13 at the Univ. of California Radiation Laboratory, on 21 U-Al fuel elements containing a total of 3,192 gm U^{235}. Its 3×10^{13} neutron flux is the highest of any West coast research reactor; when brought to full power it will operate at 1 Mw. Its two graphite thermal columns and 14 beam holes will be used for research in chemistry, physics and biology. Cost to AEC for the reactor and associated labs, utilities and equipment is $675,000.

YANKEE LETS SPHERE CONTRACT

Chicago Bridge & Iron Co., builder of the Dresden station sphere, wrapped up a $1.5-million contract to build the vapor container for the Yankee nuclear station at Rowe, Mass. This sphere will be 125 ft dia, mounted on 16 supporting columns; its steel plates will weigh 1,800 tons. Delivery of plates is to start in July, erection later in the year for mid-1959 completion. Preliminary site work is underway.

TREAT TO BE STARTED THIS SPRING

Another reactor for the National Reactor Testing Station in Idaho, TREAT (Transient Reactor Testing facility), will be placed in construction by Argonne National Laboratory's Idaho division early this year. Bids are due Jan. 20 on construction of the reactor and control buildings and related services, estimated to cost about $450,000. The facility will test to destruction fuel elements for breeder reactors.

MARTIN PACKAGE POWER PROGRESSES

Martin Co.'s critical facility went critical last month with the core designed for its package power reactor. The core loading was ~700 stainless-clad, enriched-U fuel tubes. Tests of the fuel element at the Materials Testing Reactor showed 41.7% burnup after 11 months' irradiation, retention of structural integrity, and freedom from deterioration, distortion or blistering.

LOCKHEED TO ENTER POWER REACTOR FIELD

Lockheed's Georgia division will design and build nuclear reactors for power and heat at its Marietta, Ga., plant, according to its general manager, Carl Kotchian. Several proposals are being submitted seeking contracts "on the basis of our own designs and research developments," says Kotchian. The Georgia division is also building a nuclear research lab for the Air Force near Dawsonville; the test reactor there is slated to go critical late this year and to start full operations in March 1959. As present indications show the Air Force will not use the facility's full capacity, additional radiation test work is being sought.

ANOTHER WESTINGHOUSE CARRIER JOB

A $46-million contract for design and fabrication of "reactor compartment components" for the first nuclear-powered aircraft carrier has gone to Westinghouse, the Navy announced; it added that the contract covers "such items as instrumentation, controls, valves and pumps." Westinghouse has earlier contracts for the ship's eight reactor pressure vessels and 32 steam generators, and for its main propulsion machinery.

News in Brief

Argonne Gets 12.5-Bev Accelerator

After long consideration, AEC has authorized construction of a $27-million, 12.5-Bev proton accelerator at Argonne; $1.5-million has been made available for detailed designed work. The machine, when completed in 1961–62, will produce a greater number of accelerated particles than any of the other big accelerators built or building anywhere in the world, AEC says, although two now under construction will have higher particle energies: AEC's Alternating Gradient Synchrotron under way at Brookhaven since 1954, and a similar unit being built in Geneva by the European Organization for Nuclear Research (CERN), which are in the 25–30-Bev range. On their completion in 1960, they will be the world's most powerful accelerators. Russia has recently placed in operation a 10-Bev accelerator.

AEC action on the Argonne machine caps a two-year rivalry between Argonne and Midwestern Universities Research Association (MURA) (NU, March '56, 18). MURA has wanted AEC to build a new advanced type of accelerator it has designed, at its own site at Stoughton, Wis.; it would have an energy equivalent of a trillion electron volts. In a conciliatory statement, AEC pointed out it has already given MURA $2-million for its studies; that the MURA machine would cost $100-million and take 5–7 years to build instead of the 4–5 of the 12.5-Bev Argonne unit; but that if MURA demonstrates the technical feasibility of its design, AEC will consider building it. Even then, however, because of the "large supporting facilities in many scientific fields" required, AEC would favor the Argonne site where such facilities are already in existence.

Food Irradiation Center Plans Go On

In spite of the closing out of the Food Irradiation Reactor project (NU, Nov. '57, 22), work is continuing on the Army Quartermaster Corps' food irradiation research center at Stockton, Calif. Irradiated Products Inc.—a joint venture of Armour & Co., Continental Can Co., General Foods Corp. and Food Machinery & Chemical Corp.—has received a Defense Dept. contract for production planning of the center, including layout, design, and production methods. The plant will consist primarily—now that the reactor has been eliminated—of an electron accelerator and a gamma source.

World Radiation Research Congress Set

The National Academy of Sciences – National Research Council and the Radiation Research Society are organizing an International Congress of Radiation Research at Burlington, Vt., Aug. 10–16, 1958. It is expected to bring together 150 leading researchers in radiobiology, radiation chemistry, radiation physics and radiology from 30 countries to discuss the Congress' objective: understanding of the processes of interaction of radiation and matter. Although having the cooperation of AEC, the Department of State and the National Science Foundation, the organizers feel it essential that sponsorship reside in private scientific groups, and are seeking to raise $40,000 of the total $75,000 budget from industry and private sources. Contact John S. Coleman, National Academy of Sciences, Washington.

Forum Sponsors 'Nuclearama'

An international traveling exhibit of atomic industry equipment called Nuclearama, aimed at technical and management audiences, is being organized by the Atomic Industrial Forum. "Manufacturers of equipment, components, nuclear materials, essential accessories and directly applicable services" may contract for one to four 6-×-4-ft panels carrying exhibits about their products or services. Nuclearama will be shown a minimum of five times during the two-year contract period; it has already been scheduled for the 1958 Geneva conference and the 1958 Forum annual meeting.

PRDC Hearing Record Closed

AEC Hearing Examiner Jay A. Kyle has finally closed the hearing record on the Power Reactor Development Co. case and certified it to the Commission, which now has the case under consideration.

Plan Study on A-Power Development

The Twentieth Century Fund is undertaking an examination of the economic need for nuclear power in the U. S., and its relationship to U. S. ability to meet international demands in this field. Research director of the study is Philip Mullenbach, a former AEC economist more recently research director of the National Planning Assn.'s nuclear energy project.

AEC Adopts More Stringent Exposure Limits

The new, lower maximum permissible radiation exposures recommended by the National Committee on Radiation Protection (NU, Jan. '57, R3) have been approved for use by AEC in its facilities and those of its contractors. "No appreciable modification of present radiological safety practices will be required," AEC says, to put the new standards into effect.

Graver Low Bidder on EBR-2 Job

Graver Tank & Mfg. Co. was apparent low bidder, at $663,547, of seven firms seeking to build the outer containment shell for AEC's Experimental Breeder Reactor 2 at the National Reactor Testing Station in Idaho. The vessel is to be 80 ft dia, 139 ft high, of 1-in. carbon steel plate; the job includes excavation of a pit for the building shell and construction of a 200,000-gal water storage tank.

Insurance Study for Forum at Harvard

Harvard Law School has started a study for the Atomic Industrial Forum of international aspects of providing financial protection to the public and to industry against nuclear risk. The Forum last year published a report by Columbia Law School on domestic aspects of the nuclear insurance problem.

Reactor Zirconium Price Slashed

Carborundum Metals Co. has announced a new price for reactor-grade zirconium sponge: $7.50/lb in 1,000-lb lots. This is the third major Zr price reduction by Carborundum since 1953, when the price was $22/lb.

AGN Nucleonics a Wholly-Owned Subsidiary

Aerojet-General Corp. has acquired 100% ownership of its subsidiary Aerojet-General Nucleonics, in which it formerly held about 80% ownership. No change is planned in location, policy, officers or management of the subsidiary, which has grown from 25 scientists and technicians in July 1956 to 150 today.

Isotope Statistics Now On Licensing Basis

Reflecting the coming of age of radioisotope use, AEC is shifting its isotope-distribution statistics from an authorization to a licensing basis.

From Aug. 2, 1946, to Feb. 10, 1956, isotopes were dispensed under an AEC authorization procedure. In that period 3,100 organizations were authorized to use isotopes. On Feb. 10, 1956, the authorization procedure was changed to a more formal licensing procedure, and the task of converting authorizations to licenses was begun. Because this process is now more than 90% complete, and because the licensing procedure has been in effect for nearly two years, AEC is converting to a licensing report.

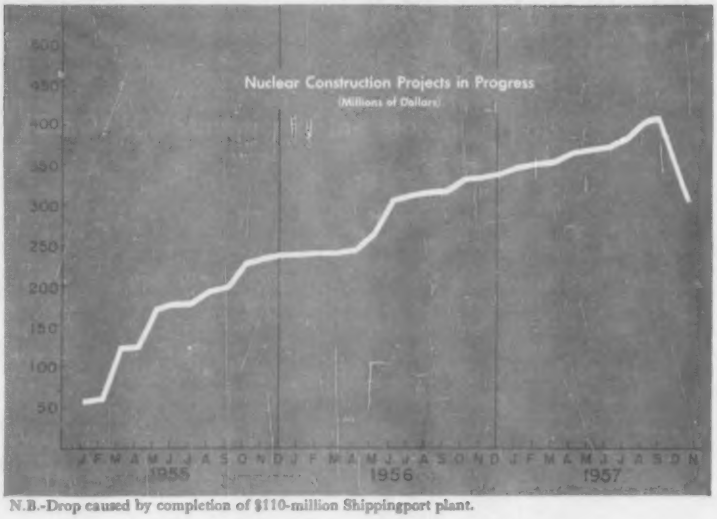
The October 1957 monthly report stated that 4,353 organizations had been authorized, or licensed, since the beginning of the program. The November report, first under the new system, shows only 3,335 organizations licensed. The total number now holding valid licenses is lower for these reasons:

1. Large institutions at multiple locations, previously holding several authorizations, have been issued a single basis license. (Indeed, this is one of the purposes of the licensing procedure.)
2. Several authorizations still await conversion.
3. During the nearly 12 years of radioisotope utilization, some organizations have discontinued their use.
4. The quantities of isotopes available under general license (Code of Federal Regulations, Title 10, Part 30, section 30.72) have been increased; several users purchase isotopes under general license without need for a specific license, and are thus not included.

Westinghouse Billings, Backlog Both Up in 1957

Westinghouse billings for 1957 in the atomic power field will nearly double those of 1956, Chairman Gwilym A. Price declared in his year-end statement, and at the same time backlogs are expected to be higher. Much of this backlog is for the nation's nuclear-powered Navy, "but a build-up can be expected in the commercial field also," he said, "even though it will take some time before atomic power will be able to compete."

NUCLEONICS Statistics of the Month



N.B.-Drop caused by completion of $110-million Shippingport plant.

	Latest month	Month ago	Year ago
Nuclear Contracts*—			
Contracts awarded for federal projects ($10³)	3,354	9,583	735
Proposed construction, privately-owned ($10³)	17,000	0	1,000
Contracts awarded, private work ($10³)	30,500	9,500	0
Backlog of private projects ($10⁶)	243	226	168
Access Permits†—			
Access permits issued	25	25	39
Total access permit holders	1,396	1,381	1,114
Isotope Use†—			
Applications for isotope use	339	344	454
Cumulative total of isotope users	3,335¶	4,353	3,624
Oak Ridge National Laboratory shipments	1,134	1,201	1,142
Public and private export shipments	167	407	157
Employment†—			
AEC employment	6,832	6,852	6,626
Construction and design contractors' employment	11,627	11,581	15,043
Total operating contractors' employment	97,925	99,150	92,832
Production workers	50,285	50,577	49,589
Research and development employees	41,305	41,822	37,277
Miscellaneous workers	6,335	6,751	5,966

	Operating	Building	Contracted
U. S.-built Reactors‡—			
Power, domestic	2	4	8
Power, for export	0	1	5
Power experiments	6	3	3
Military and naval	5	20	10
Research and test, domestic	41	26	38
Research and test, for export	6	15	4
Foreign-built Reactors‡—			
Power, domestic	4	24	12
Power, for export	0	0	2
Research and test, domestic	24	17	6
Research and test, for export	3	9	1

* From *Construction Daily*, a McGraw-Hill periodical † From AEC ‡ NUCLEONICS figures
¶ See story at left.

New Instrument News

Operation and Selection of "RCLiac" Scaler-Analyzers

General Description

The "RCLiac" scaler-analyzers are innovations to nuclear data processing. Nuclear detector pulses are processed and quantized in total or in spectra.

Operation and Application

Two basic modes of operation yield extensive applications in the laboratory. Gross counting, the scaler mode of operation, affords events-per-interval-of-time or time-per-event analysis. Time intervals or event totals may be preset. Simple applications in this mode of operation are: half-life determination, pulsed reactor response, fast-neutron velocity distribution, and other similar studies. With the aid of an automatic sample changer, as many samples as there are channels can be counted, automatically.

The spectrometry mode of operation allows background reduction, smaller tracer doses, isotope identification, complex spectral distribution analysis and other related analyes.

With their inherent versatility of operation and application the RCLiacs are believed to be destined to become as universally accepted in the nuclear field as the oscilliscope is in the electronic field.

Readout

The RCLiacs have two basic readout modes, "Curve" and "Number". "Curve" readout plots graphically the total count recorded in each channel. "Number" readout displays the arithmetic total of counts received in each channel in decimal Arabic form. Both RCLiac models have switch-selected "Curve-Number" readout displayed on a cathode-ray tube which presents a photographic image for rapid and accurate recording of data for permanent reference.

Design

Reliability, precision and ease of operation have been designed into the RCLiacs. Design features which contribute to these parameters of operation are: 95% transistorization affording greater reliability and lower power requirements, printed circuitry throughout and modular construction affording unique adaptions for specific situations. Yet the RCLiacs are remarkably small in size and weight, actually portable.

Selection

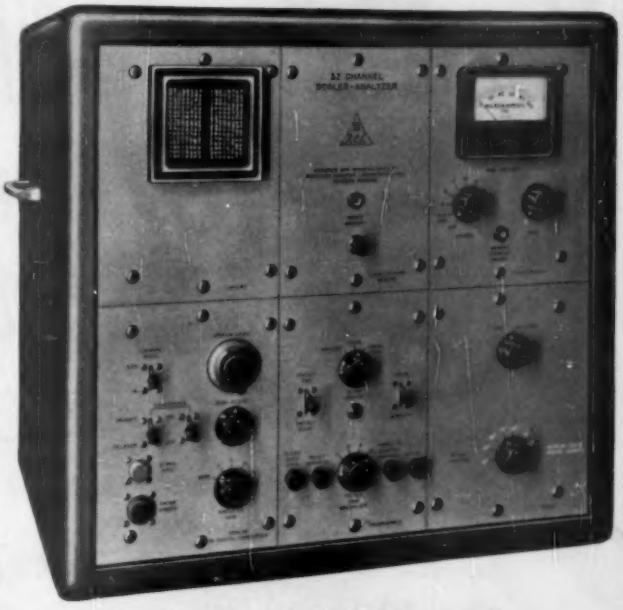
Selection of your RCLiac should be based primarily on your facility's basic research requirements. For the modest laboratory the RCLiac-32 should be considered, while larger installations may require the RCLiac-128. The RCLiac-128 has four times the range of the RCLiac-32, affording a greater energy range in the spectrometry mode and a greater range of operation in the gross counting mode.

The finest spectrometry instrument now in use is the RCL 256-channel analyzer, the most widely accepted instrument for pulse-height analysis.

Your RCL representative can offer excellent counsel and help you in the proper selection of the right RCLiac for you. Write today for more detailed information on the RCLiacs and a list of representatives near you.

Introducing

RCLiac-32 and 128



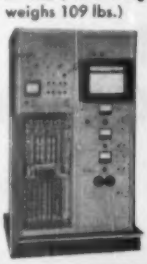
transitorized multi-channel scaler-analyzer data processing systems

One instrument that performs all operations from detection to qualitative or quantitative analysis. All counting and analytical operations from simple gross counting through scintillation spectroscopy and pulse-height analysis can be accurately and rapidly processed by the RCLiacs.

The RCLiac-32 and the RCLiac-128 are basically the same, the major difference being the number of channels.

Reliable operation is guaranteed by transitorization, printed circuitry, plug-in modules and a magnetic core memory. Design features include: built-in power supply with negative voltage continuously variable from 500 to 1500 volts; maximum input pulse rate of 50,000 cps.; preset time for analyzer or scaler functions; and decimal arithmetic circuits which can count to 10^6 and add or subtract without complementing or other complex operations.

Input power, one ampere, 105-120 volts, 50-60 cps. Dimensions, 20" x 21½" x 18½", and weight, 102 lbs. for the RCLiac-32, assure portability. (RCLiac-128 weighs 109 lbs.)



RCL's 256-Channel Analyzer

For the research laboratory that needs the full range of 256 channels, the precision and accuracy of the RCL-256 are unmatched. New features: interpolation lights which aid in setting the zero point; dead time corrected for up to 27 hours of continuous operation; decimal conversion with direct channel identification; readout presented via cathode-ray tube display and a Hewlett-Packard 560-A printer (original equipment).

© Radiation Counter Laboratories, Inc.

NUCLEONIC PARK, SKOKIE, ILLINOIS

Radiation Counter Laboratories, Inc. Dept 118
Nucleonics Park, Skokie, Ill.

Gentlemen,

Please send me information on the ☐ RCLiac-32, ☐ RCLiac-128, ☐ RCL's 256 Channel Analyzer.

Name_____

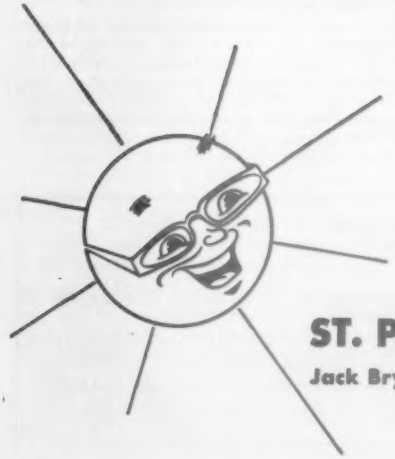
Address_____

City_____ State_____

MAKE YOUR MARK

in greater St. Petersburg

where work and play are combined—



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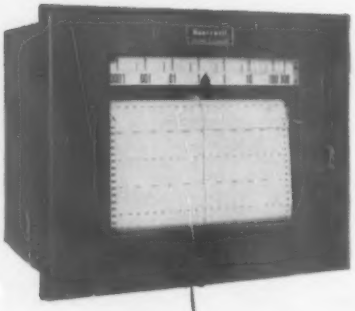
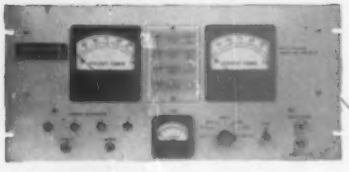
economic analysis • plant location • engineering • design • procurement • expediting • construction

ElectroniK recorders . . . with special scales for nuclear process variables.

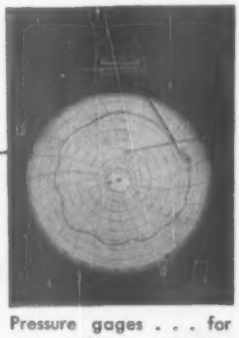


MegopaK thermocouple wire . . . designed for fuel element temperatures in nuclear installations.

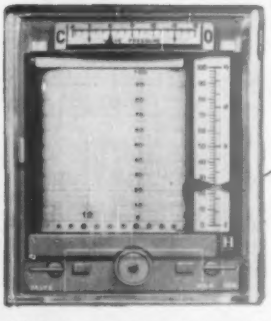


Safety amplifiers . . . one of eight special units for reactor control.

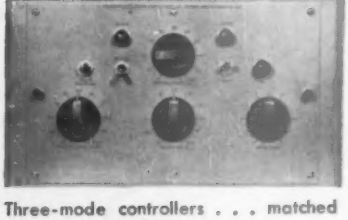
from ONE source



Pressure gages . . . for coolant flow, monitoring, and other applications.



Tel-O-Set miniature instruments . . . for use on graphic panels or to save space.



Three-mode controllers . . . matched to reactor characteristics.

. . . reactor instrumentation for every need

What are your instrumentation requirements—a single instrument . . . a packaged nuclear reactor control system? You can place undivided responsibility with Honeywell for everything from initial specifications to complete installation and startup.

From this one source, the world's largest instrument manufacturer, you also receive expert engineering assistance in application and maintenance . . . and prompt, efficient service from a branch office near you.

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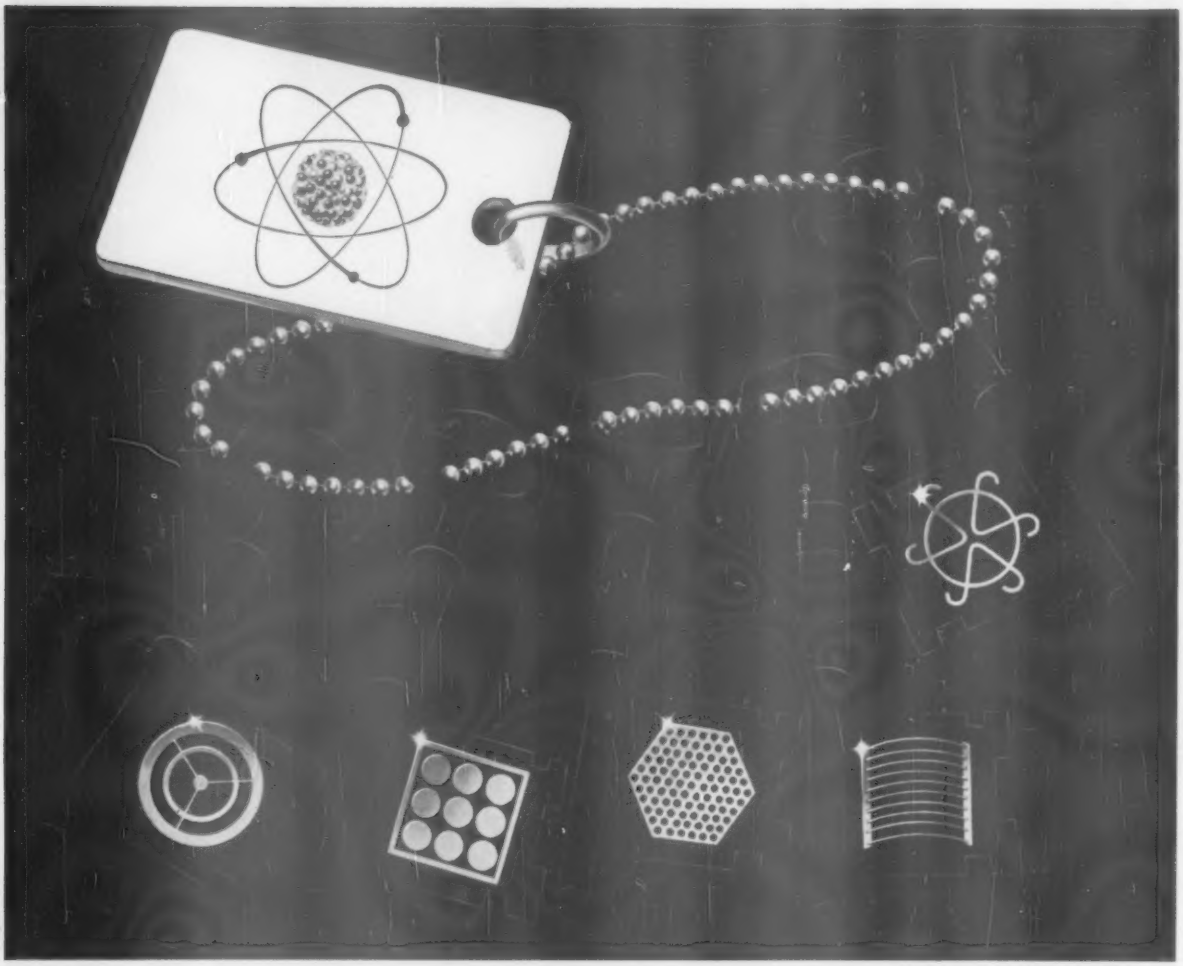
BRINGING TOMORROW CLOSER WITH NEW METALS



Which is the key to economical nuclear power?

In any reactor, economical power production depends a great deal upon the design, composition and construction of the fuel element itself. Shape, size, mechanical structure and degree of enrichment all play a part in the extraction of maximum energy with minimum fuel cost.

Sylvania-Corning was a pioneer in the development of efficient reactor fuel elements and practical reprocessing techniques. During more than eight years of successful experience in solving advanced technical problems in atomic energy, they have built up a unique and highly specialized research organization. Staffed with top-ranking scientists and engineers, working in well-equipped laboratories, Sylvania-Corning carries on a constant program of reactor fuel research in four basic fields: materials, fabrication and test development and fuel-element production.

Particular stress is laid upon the development of test methods—both in and out of reactor. For only by means of satisfactory test methods can new designs and materials be evaluated. To this end, Sylvania-Corning has perfected a number of unique methods of reliable projective evaluation.

If you are wondering which type of element will prove most effective in your own reactor, we will be glad to make recommendations on the basis of our long and specialized experience in nuclear fuels. Sylvania-Corning Nuclear Corporation, Bayside, N. Y.

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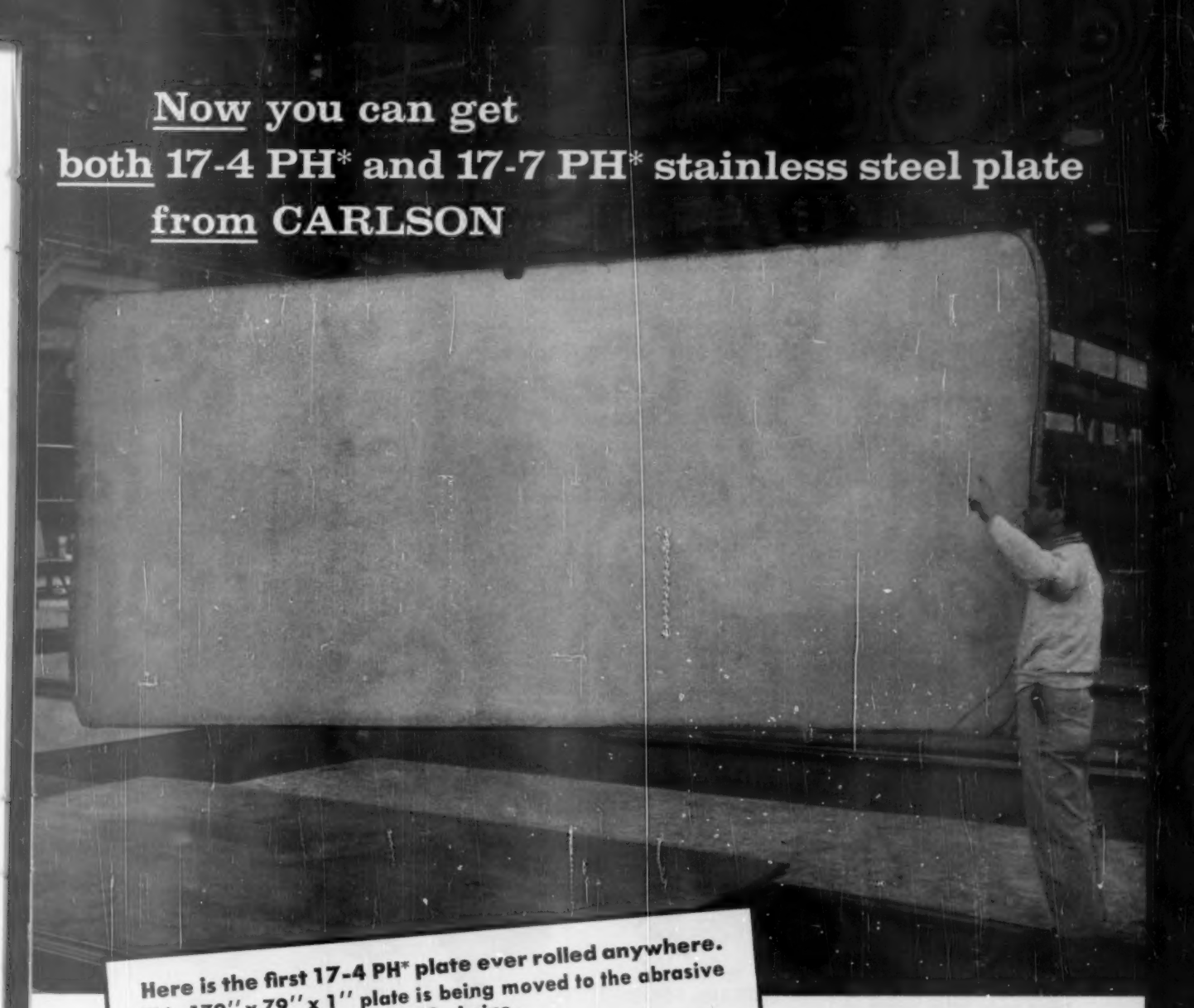
Now you can get both 17-4 PH* and 17-7 PH* stainless steel plate from CARLSON



Here is the first 17-4 PH* plate ever rolled anywhere. This 179" x 79" x 1" plate is being moved to the abrasive cutters for trimming to specified size.

You can build equipment with either of two precipitation-hardening stainless plate grades—17-4 PH* and 17-7 PH*. Both are available at Carlson—both can be cut to your exact specifications to save delays and true-up time in your own plant.

The Armco-developed 17-4 PH and 17-7 PH grades combine ease of fabrication, hardenability, high strength and corrosion resistance. These grades have the desirable mechanical properties of the hardenable chromium types and a workability and corrosion resistance approaching regular 18-8 stainless steels. Simplified low temperature heat treatments will produce a Rockwell hardness of C40 to C50. And tensile strengths range from 180,000 to 215,000 psi depending upon the heat treatment.

Take full advantage of our complete service in stainless steel plate and plate products. Write, wire or phone for detailed information on 17-4 PH and 17-7 PH stainless steels.

*Trade Mark of the ARMCO STEEL CORPORATION

G.O.CARLSON Inc.

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District Sales Offices in Principal Cities

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World's Most Versatile Unit for Measuring Radiation

JORDAN RAMS II

Remote **A**rea **M**onitoring **S**ystem

The Basic RAMS II System

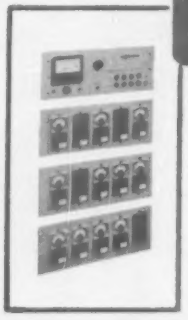
- Offers a choice of 32 standard plug-in-units available from stock to fill nearly every radiation monitoring requirement.
- Monitors up to 20 channels from ONE CONTROL panel.
- Choice of sensing elements—small chamber for high intensity (10 mr/hr to over 100,000 r/hr) or large chamber for fast response at low levels (below 10mr/hr). Chambers can be located up to TWO MILES from the Control Unit without pre-amps.
- Remotely controlled check source verifies channel accuracy at any time.

You can begin your RAMS II System with one channel and one control panel and add more channels as needed.

Station units are available with single or dual logarithmic scales of three decades each. Equally accurate measurements of true dose rate over a range of 1,000: 1 to 1,000,000: 1 are possible only with logarithmic response pioneered by Jordan.

Adding or changing station units is as simple as plugging in a tube. And, each station unit contains all indicators and controls for one channel.

Simply pressing a button on any station unit transfers the reading to the large accurate Control Panel Meter.



4 BASIC STATION UNITS

1. **INDICATING METER** for continous indication
2. **METER RELAY** to actuate alarm circuits
3. **INDICATING METER RELAY** to actuate alarms and indicate continuously
4. **NON-INDICATING** for low-budget installation . . . reading is obtained on the 4½" Panel Meter

TYPICAL APPLICATIONS:

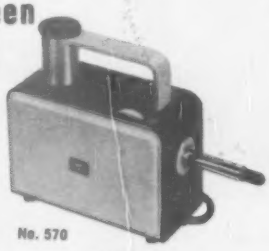
- Health Monitoring
- Level Indication
- Hot Laboratories
- Radiation Therapy
- Nuclear Reactor Projects
- Civil Defense
- Hospital Radioisotope Treatment
- Other Applications:
  1. Monitoring during & after Atomic tests.
  2. Installation near cyclotrons and other particle accelerators

Victoreen

VICTOREEN RADOCON

For Roentgenologists, Radiologists

Radocon provides positive, complete and automatic X-Ray dose control. Set pre-established dose and intensity range on Radocon, insert attached probe (ionization chamber) at body radiation site, and Radocon will monitor exposure safely, reliably . . . shutting off all equipment and signalling operator when exposure is complete. Continuous direct-reading of X-Ray and gamma ray delivery rate. Direct-reading accumulated radiation dose during exposure. Sounds alarm in event of unwanted variations in delivery rate. Avoids overdose due to personnel or equipment failure.



No. 570

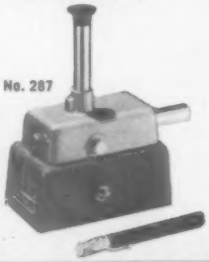
VICTOREEN CONDENSER R-METER

for POSITIVE RADIATION CONTROL

Flexible—Model 570 R-meter provides accurate, convenient and reliable radiation measurements in research and industrial labs, for chemical and food processing, and in X-Ray therapy. Uses interchangeable, easily attached ionization chambers for a wide variety of intensity and dosage requirements. Fast, positive zeroing — no trials. The name **Victoreen** is your assurance of technical perfection.

VICTOREEN MINOMETER

Model 287 Minometer is a convenient and efficient charger-reader meter for use with **No. 362 Pocket Dosimeters.** Minometer charges the dosimeters of each worker at the beginning of the work day and measures the remaining charge at the end of the work period without delay! In this way an accurate daily radiation exposure check can be made on each employee. Measures voltage drop in milliroentgens. 105-130 V, 50-60 cycle A.C. only. Stray-radiation area-type dosimeters chambers also available for No. 287 Minometer.



No. 287

JORDAN'S NEW PORTABLE RADIATION MONITOR

Your Choice of 3 models

Rigid-probe and extension-cable models are also available for special applications.

Has widest range of any survey meter. Its accurate logarithmic response from 0.01 mr/hr to 10,000 r/hr eliminates the need and expense of having a Geiger counter and both low and high range ion-chamber survey meters for Gamma and Beta measurement.

This versatile monitor with built-in check source for calibration can detect radiation at extremely low levels. Variation as low as 0.002 mr/hr may be measured near background levels. Weight 4½ pounds.

NEW JORDAN PORTABLE *Radector*

Ranges: .05 mr/hr to 500 r/hr

The well-known and widely used Jordan Radectors are simple, reliable and inexpensive instruments for detecting a wide range of Gamma and Beta radiation.

The wide range of the Radector covers intensities now measured by Geiger Counters—medium and high range ion-chamber type instruments.

For the low price of one instrument the RADECTOR performs the function of three expensive instruments, plus many other advantages • simplicity of operation • minimum training period for its use and very little maintenance or repair costs. Weight 3½ lbs.

IONIZATION CHAMBER: High pressure, argon filled. **Beta window** — 1 mil (20 mg/cm²) stainless steel. **Window opening**—equivalent to 0.5" diameter. **Beta rejection screen** — .036" steel. **Gamma ray energy dependence** — Substantially independent between 80 kev. and 1.2 mev.

Your request for technical bulletins and price quotations on Nucleonic and Electronic requirements will receive our prompt attention, without obligation.

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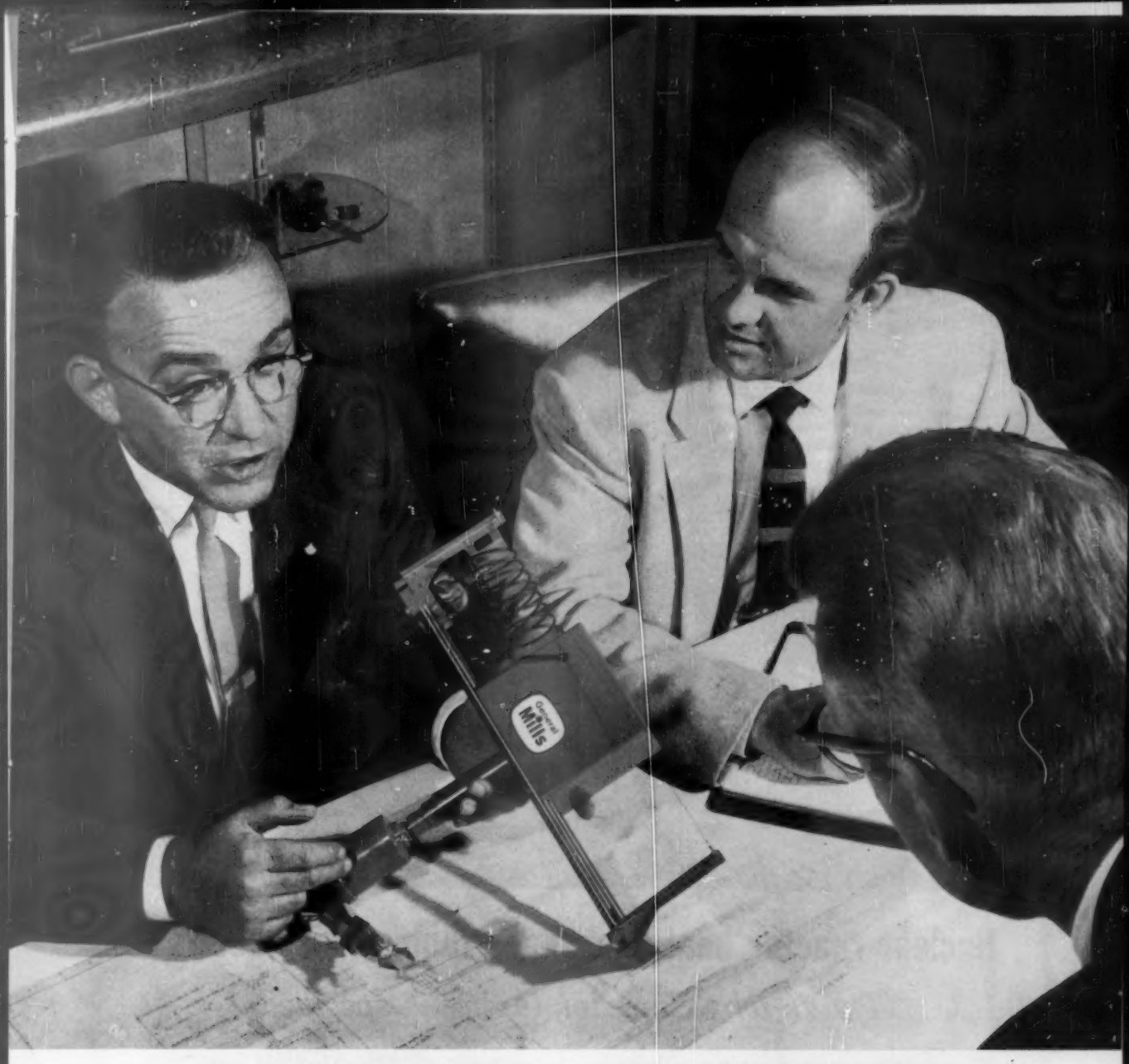

Perhaps we have already solved your nuclear handling problem

Hot cell handling problems have been met—and solved—for nearly a decade by General Mills engineers. Our fund of nuclear handling know-how is available to you. Consultation in the early planning stages of your installation could save you time and money—and result in more efficient operation.

Whether your requirement is a standard General Mills Mechanical Arm or special equipment—or if you are wondering which—contact our Nuclear Products Department, 1620 Central Avenue, Minneapolis 13, Minnesota. The phone is STerling 9-8811.

MECHANICAL DIVISION

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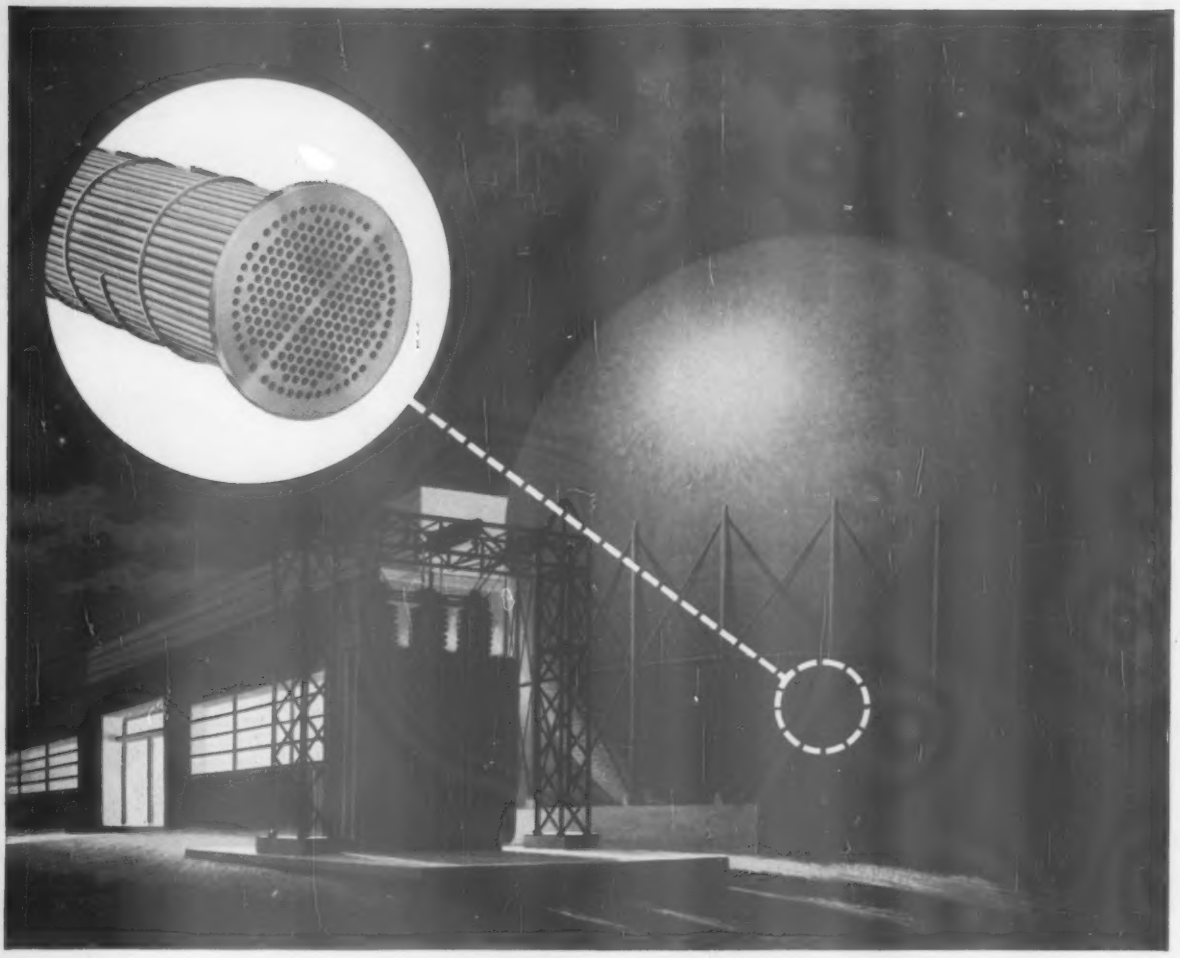
General Mills



Nuclear reactor heat exchanger tubing must not fail

That's why Superior tubing is specified

When the count starts rising in a nuclear pile and the reactor goes critical, the heat exchanger begins its vital function. Reactor heat exchangers require tubing of the highest quality.

This tubing must offer rapid and efficient heat transfer. It must be bright and clean, with extremely smooth ID and OD surfaces for uninterrupted fluid flow. Walls must be uniform throughout—no heavy sections to slow down heat transfer, no thin spots where scaling or corrosion might gain a foothold. Ductility is also important for fabrication ease. Excellent weldability is a prime requirement.

Superior has been supplying high quality tubing in a wide variety of analyses and sizes to heat exchanger manufacturers for many years. We produce to the most exacting tolerances and specifications. Get more information and free literature today on Superior tubing for atomic power. Write Superior Tube Company, 2027 Germantown Ave., Norristown, Pa.

Superior Tube

The big name in small tubing

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All analyses .010 in. to ⅜ in. OD—certain analyses in light walls up to 2½ in. OD

West Coast: Pacific Tube Company, 5710 Smithway Street, Los Angeles 22, Calif. • RAymond 3-1331

A simplified guide to select...

pumps for nuclear fluids!

The chart below offers an easy guide to proven pump types now available for nuclear fluid handling. These pumps are listed by types of fluid circulated in the three basic commercial reactor developments.

BJ Liner Motor Pump

	FLUID CIRCULATED	RECOMMENDED PUMPS AVAILABLE	PERFORMANCE RANGES
1	PRESSURIZED WATER, BOILING WATER AND HEAVY WATER	a. Liner Motor Pumps	Capacities: To 17,000 gpm Pressures: To 5300 psi Temperatures: To 700° F.
		b. Mechanically-Sealed Pumps	Capacities: To 125,000 gpm Pressures: To 2,000 psi Temperatures: To 600° F.
2	LIQUID METALS (SODIUM, BISMUTH, ETC.) *Pressures as required	a. Vertical-Inert Gas (Mechanically-Sealed)	Capacities: To 25,000 gpm *Pressures: Temperatures: To 1600° F.
		b. Vertical-Oil Filled Motor Pump (Mechanically-Sealed)	Capacities: To 5,000 gpm *Pressures: Temperatures: To 1600° F.
		c. Vertical-Gas Filled Motor Pump	Capacities: To 5,000 gpm *Pressures: Temperatures: To 1600° F.
		d. Liner Motor Pumps	Capacities: To 5,000 gpm *Pressures: Temperatures: To 1600° F.
3	ORGANIC	a. Special Process Pumps (Mechanically-Sealed)	Capacities, pressures and temperatures as required.
4	EXPERIMENTAL NUCLEAR DEVELOPMENTS	Byron Jackson's Nuclear Pump Section is ready to assist you in new development projects. All of the above pump types are available and new designs can be created for experimentation.	Capacities, pressures and temperatures as required.

World's largest Liquid Sodium Pump

ONLY BYRON JACKSON designs and manufactures nuclear pumps and mechanical shaft seals to answer all nuclear fluid handling requirements. BJ Pumps are in use or on order for almost all major commercial reactor developments in the United States. This broad background in nuclear pumping methods can help you find the best answer to your small or large nuclear pumping requirements... with important savings in time and money.

BJ Special Process Pump for Organic Fluids

BJ SINCE 1872

BYRON JACKSON PUMPS

INCORPORATED

A Subsidiary of Borg-Warner Corporation

BOX 2017A, TERMINAL ANNEX · LOS ANGELES 54, CALIFORNIA

¼ HP, 2000 PSI Liner Motor Pump

PHILIPS *equipment for*
Nuclear Physics and Atomic Energy

Shown here is a 4-stage cascade accelerator, which supplies a heavy particle beam of 1 mA at a voltage of over 700 kV. Similar units can be supplied for other energy ranges. Accessory equipment such as electronic stabilizers keeping the accelerating voltage constant within 1:1000, beam deflecting magnets, etc. are available if required.

- Synchro-cyclotrons for various final energies.
- Linear electron accelerators.
- Cockcroft-Walton accelerators.
- Radiation measuring equipment.
- Area monitoring instrumentation.
- Civil defence instruments.
- Reactor control instrumentation.
- Geiger counter tubes.
- Radio-active isotopes.
- Air liquefiers.
- Generators for very high d.c. voltages.

4-stage compact cascade accelerator installed at the Physikalisch Technische Bundesanstalt in Brunswick, Germany.
(Photo by courtesy of P.T.B., Brunswick).

PHILIPS

Nuclear Equipment

For further information please apply to one of the following addresses:

N.V. PHILIPS' GLOEILAMPENFABRIEKEN,
Scientific Equipment Department, Eindhoven - Holland

PHILIPS ELECTRICAL LTD.,
Research and Control Instruments Division, Shaftesbury Avenue, London W. C. 2

PHILIPS ELECTRONICS INC.,
Instruments Division, 750, South Fulton Avenue, Mount Vernon N.Y. U.S.A.

PHILIPS

one of a series... ANNOUNCING H&N's NEW NUCLEAR DIVISION

Kelly McBean, Manager of H&N's new Nuclear Division, tells
"What We Learned on Eniwetok About

The Strange Structures that Test Atomic Safety"

"To the eye, this atom age structure is little more than a bleak and faceless building. Yet its seemingly characterless masses of concrete must be meticulously designed. Nine years of continuous experience in the design and construction of the AEC's Eniwetok Proving Ground, plus two years of exhaustive research in the States, has taught us that *nuclear safety requires engineering concepts that are new to industrial design and construction.* Also required is an unprecedented union of specialized science with experienced engineering. Our Nuclear Division offers both, focused on the safety of industrial nuclear facilities in all its aspects, from the nuclear characteristics of the source to the integrity of shielding and containment."

HOLMES & NARVER's long experience with nuclear test facilities has involved massive problems in radiation shielding and blast-resistant construction. Although Eniwetok test data cannot be translated directly into industrial radiation containment concepts, the engineering method can—and the proof of these design methods under maximum radiation and maximum pressure assures more confident safety predictions. But confidence in safe design depends first on sure knowledge of the forces creating the hazard. At Eniwetok, as in your plant, this means the nuclear physicist and the engineer attack the radiation problem together. Our Nuclear Division includes a nuclear physicist who has specialized in reactor hazard evaluation, in all known concepts. The firm invites consultation on special safety problems—or the full responsibility—from plan to finished plant.

A new booklet, "Nuclear Safety," is available upon request

Holmes & Narver, Inc.

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SERVING THE ATOMIC ENERGY PROGRAM SINCE 1948

HIGH PURITY RARE EARTHS

Available in quantities at surprisingly low cost

a report by LINDSAY

A few months ago, in one of these reports, we presented this table of high purity rare earth and yttrium oxides. We anticipated inquiries, of course, but the flood of letters requesting detailed information really startled us.

What interests us particularly, and will you, is the fact that so many research people are intrigued with the practical possibilities of these unique materials. The large amount of research now being done on high purity rare earth oxides in a wide variety of industries encourages us to suggest the likelihood that they may offer you opportunities for potentially profitable investigation.

Already, in a little more than two years since rare earths in purities up to 99.99% became available in commercial quantities, they are being used as basic production materials in many chemical and industrial operations.

Production Up—Costs Down

We have expanded our production facilities to keep up with demand and now have more than 100 ion exchange columns in continuous operation. Quantities are large enough to assure you a dependable source of supply. Prices are low enough to make their use on a production basis economically sound.

Most of the high purity rare earth and yttrium oxides are available for prompt deliveries in quantities of an ounce to hundreds of pounds.

We can't tell you how to use high purity rare earths in your production operations, nor can we promise that one of them may be the missing element in new process or product developments on which you are working. We *can*, however, supply you with data which you will find interesting, revealing and quite possibly of immediate importance to you.

TYPICAL MAXIMUM IMPURITIES IN LINDSAY PURIFIED RARE EARTH AND YTTRIUM OXIDES

ATOMIC NO.	OXIDE	CODE	PURITY	% RARE EARTH MAXIMUM IMPURITIES AS OXIDES
57	La_2O_3. LANTHANUM OXIDE	528 529	99.99 99.997	0.01 Pr, 0.001 Ce. 0.0025 Pr, 0.0005 others
58	CeO_2. CERIC OXIDE	215 216	99.8 99.9	0.2 (largely La + Pr + Nd). 0.1 (largely La + Pr + Nd).
59	Pr_6O_{11}. PRASEODYMIUM OXIDE	726 729.9	99 99.9	1 La + Nd + smaller amounts of Ce and Sm. 0.1 Ce + Nd.
60	Nd_2O_3. NEODYMIUM OXIDE	628 629 629.9	95 99 99.9	1-4 Pr, 1-4 Sm, 0.5-1 others. 0.1-0.4 Pr + 0.1-0.4 Sm + 0.5 others. 0.1 (largely Pr + Sm).
62	Sm_2O_3. SAMARIUM OXIDE	822 823	99 99.9	0.2-0.7 Gd, 0.2-0.6 Eu, and smaller amounts of others. 0.1 (largely Nd + Gd + Eu).
63	Eu_2O_3. EUROPIUM OXIDE	1012 1011	98-99 99.8	1-2 Sm + smaller amounts of Nd + Gd + others. 0.2 (largely Sm + Gd + Nd).
64	Gd_2O_3. GADOLINIUM OXIDE	928.9 929.9	99 99.9	1 Sm + Eu + trace Tb. 0.1 Sm + Eu + trace Tb.
65	Tb_4O_7. TERBIUM OXIDE	1803 1805	99 99.9	1 Gd + Dy + Y. 0.1 Gd + Dy + Y.
66	Dy_2O_3. DYSPROSIUM OXIDE	1703 1705	99 99.9	1 (largely Ho + Y + Tb + small amounts of others). 0.1 Ho + Y + traces of others.
67	Ho_2O_3. HOLMIUM OXIDE	1603 1605	99 99.9	1 (largely Er + Dy + small amounts of others). 0.1 Er + Dy + traces of others.
68	Er_2O_3. ERBIUM OXIDE	1303 1305	99 99.9	1 Ho + Dy + traces Yb and Y. 0.1 Ho + Tm.
69	Tm_2O_3. THULIUM OXIDE	1405 1403	99.9 99	0.1 Er + Yb + trace Lu. 1 Er + Yb + trace Lu
70	Yb_2O_3. YTTERBIUM OXIDE	1201 1202	99 99.9	1 Er + Tm + trace Lu. 0.1 Tm + trace Lu + Er.
71	Lu_2O_3. LUTETIUM OXIDE	1503 1505	99 99.9	1 Yb + Tm + traces of others. 0.1 Yb + Tm + traces of others.
39	Y_2O_3. YTTRIUM OXIDE	1112 1115 1116	99 99.9 99.9+	1 Dy + Gd + traces Tb and others. 0.1 Dy + Gd + traces Tb Approx. 0.05 Dy + Gd.

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Step 3 in producing commercial boron 10...

Nickel and Monel overcome corrosion by boron and potassium fluorides

Because of its high neutron absorption properties, Boron-10 isotope is now being made commercially available in the form of a 92% concentrate.

The concentrate is produced by Hooker Electrochemical Co. (contract operator for the AEC) in an AEC-owned plant designed and constructed by Singmaster and Breyer. A four step process involving fluorine and fluorine compounds is used.

To overcome corrosion from fluorine compounds, Hooker has made wide use of Nickel and its alloys. In steps 1 and 2, the formation of a liquid BF_3 complex and its fractionation into B_{10}-rich and B_{11}-rich constituents, Monel* nickel-copper alloy provides the principal corrosion protection. In Step 4, the electrolysis of KBF_4 into elemental B_{10} at 760°C, the cathode is Monel alloy and the carbon anode is contained by an Inconel* nickel-chromium alloy shell.

Step 3 converts B_{10}-rich BF_3 complex to potassium fluoborate

In this step, the dimethyl ether–BF_3 complex is dripped into a mixture of potassium fluoride hydrate, ethanol and water to form potassium fluoborate. To speed the reaction and aid in driving off side products, heat and agitation are used. The reactor is the Inco Nickel kettle shown near top of photograph. Here pure Nickel not only prevents corrosion. It aids product purity, too.

Monel alloy is used for the filter (below kettle) and drying tray (at left of workman).

Nickel alloys have outstanding record in fluorine handling

Nickel and its alloys consistently perform well in environments containing fluorine and fluorine compounds. They have outstanding resistance to corrosion by these chemicals and excellent general resistance... to other chemicals, to heat, to cold, and to mechanical damage of all kinds.

Inco's Development and Research Division will be glad to help you explore their possibilities.

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INCO NICKEL ALLOYS

NUCLEONICS JANUARY, 1958

Jerome D. Luntz, *Editor*

From Stagg Field to Shippingport

THREE YEARS ELAPSED between the discovery of fission in 1939 and the divergence in 1942 of the world's first nuclear chain reactor. In another three years, 1945, the first atomic bomb was detonated. Then, on December 2, 1957, 15 years after Fermi's success, the world's first full-scale nuclear power station built for power production went into operation at Shippingport, Pa.

The 1942 and 1945 achievements were made in time of war. Time was of the essence, and cost was not paramount.

In the years that it took until the first large-power-reactor project was initiated—in 1953—the scale of values was reversed. Time was *not* of the essence, and cost *was* paramount. There was no substantial clamoring for major shifts in the size and scope of the reactor program.

Now values are changed again, and Shippingport has come on the line at a time when its significance must be examined in the light of current pressures to move the U. S. to the fore in science and technology, and particularly in nuclear energy.

Present values indicate that the U. S. needs to shift the orientation of its nuclear power program to serve the foreign policy objectives of the U. S. better. The U. S. also needs engineering experience badly so that nuclear power costs can be lowered. Both needs must be filled fast.

More than anything else, however, we need realism in our search for answers to the problems of the day. Nothing of any substance has happened in nuclear technology in the past several months to cause any real change in the health of the industry. Forecasts of the realists of a decade ago accurately reflected the over-all situation of today.

But, unfortunately, those who have always invested the atom with an aura of unrealism have used recent statements on reactor costs as the basis for pessimistic pronouncements about where atomic energy is going.

Take Shippingport as an example of how unsound this point of view is. The initial capital and operating costs of the plant are meaningless in terms of understanding nuclear power economics. Although it's not usually considered as such, Shippingport is really a large, experimental facility. It's a laboratory. It is said to have been constructed to advance nuclear power technology generally rather than solely for the purpose of developing the pressurized water reactor.

All this costs money. And so Shippingport is expensive. But the fact is that it is a "reactor on the line." And it's a big one.

It will bring us vast engineering experience. And so will the other reactors that are coming into operation. It is the experience—hardware—stage that we're now entering, the stage that will provide realistic performance data for the first time.

It is inevitable that atomic energy—nuclear power—will pay off for the U. S. and for the companies and people working in the field. Nuclear power is needed and will be needed in large quantities in the U. S. and in many parts of the world. And the U. S. must and will step up its efforts to serve these needs. Those who have the faith, ability, vigor and imagination to stay the route will reap the benefits.

A NUCLEONICS REPORT

Understanding Nuclear Power Costs

The economic problems of nuclear power are proving almost as refractory as the engineering problems once seemed. The two are related of course, but today questions concerning nuclear power are more often cast in terms of cost.

To shed light on these economic matters, NUCLEONICS offers this special report on Understanding Nuclear Power Costs. On this page J. A. Lane reviews the present status of the field as a whole. On p. 48 W. K. Davis sums up the AEC's viewpoints on costs and on p. 50 NUCLEONICS reports on the findings of a special symposium on fuel costs. Finally on p. 54 H. L. Hollister and A. J. Burington provide insight into the whys and wherefores of the official price scale for enriched uranium.

Where We Stand Today

By JAMES A. LANE
Oak Ridge National Laboratory, Oak Ridge, Tennessee

AT THE PRESENT TIME one can foresee nuclear plants which, if everything works right, will produce power at very low cost. Nevertheless the economic picture is influenced so very strongly by factors that are difficult to evaluate, that the estimated cost of power still depends mainly on whether one wants to be optimistic or pessimistic. We need real operating experience on the prototype reactors now being constructed before we can say that the low-cost-power projections are truly realistic. Available data, however, indicate that 10-mill nuclear power in the U. S. is still a possibility in the not too distant future.

Capital Costs

The relation of current capital cost estimates to the original estimates is shown graphically for the major nuclear projects in the figure* on p. 47. A trend toward higher costs is clearly evident. It is interesting to note that in no case has an original estimate been revised downward.

These higher unit costs emphasize the difficulty of predicting plant costs in the absence of detailed designs and previous construction experience. Information based on the construction of first-generation reactors clearly indicates that manufacturers are encountering problems more difficult than anticipated and in view of this are raising bids to allow for adequate contingencies. The period of "buying into the reactor business" seems to be coming to an end.

TABLE 1—Costs in Large-Scale Plants

	Cost estimates (mills/kwh)	
Reactor	*1955*	*1957*
Yankee Electric	9.7†	11.3–14.1*
Comm. Edison	7.7‡	10.5–13.1*
U. K. Civil Stage I	4.6–6.7‡	10.8–13.6*
Shippingport	52	65†
Thorium breeder	6.5–7.3‡	9.9–13.4†
Chalk River	7.2§	5.3§

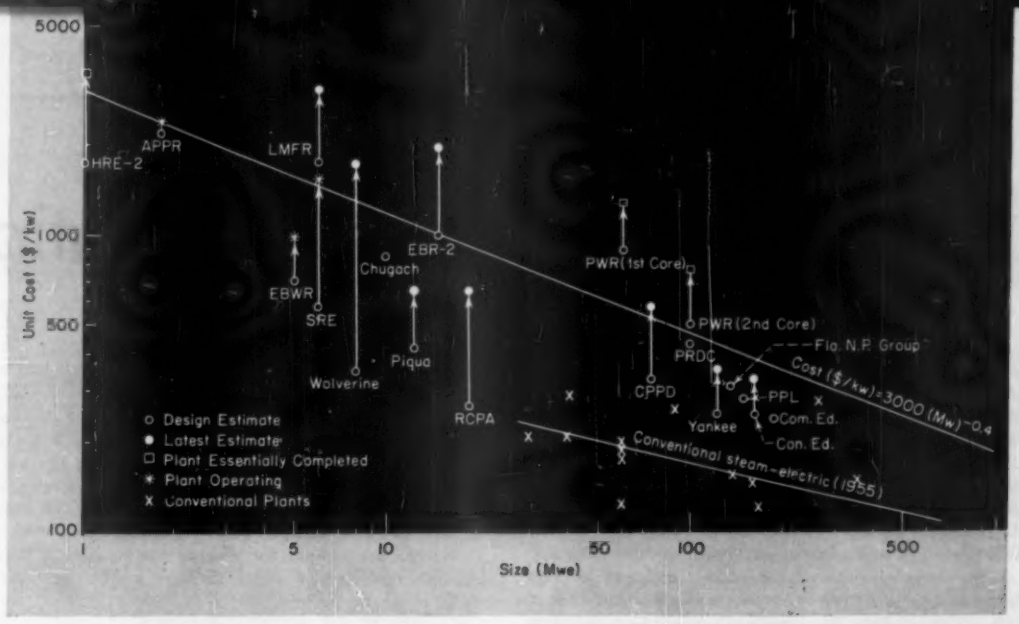
* "A Target for Euratom" (May 1957)
† Calculated from available data
‡ "Economics of Nuclear Power" (Pergamon Press, 1956)
§ W. B. Lewis, NICB conference (March 1957)

Fuel Costs

Because capital costs appear likely to be high even in the second- and third-generation plants, the future of economic nuclear power would seem to depend largely on the prospect of achieving low net fuel costs. Our ability at this time to make realistic estimates of fuel costs is even more limited than in the area of capital costs. Indications are, however, that (see p. 50) the conventional solid-fueled low-conversion-ratio reactor will have a rough time meeting the national average fuel cost of 2.7 mills/kwh for coal-fired plants. Although the influence of reactor by-products, other than fissionable material, cannot be discounted, so far such by-products have not had an important influence on nuclear power costs.

It appears that the most promising

* Presented by W. K. Davis at the Atomic Industrial Forum, October, 1957.



CAPITAL INVESTMENT COST trends are shown by plot of capital costs for U. S. power reactors. Arrows show relation between original design estimate and latest information. Latest figures lie closer to straight line representing theoretical relation between investment cost/kw and reactor power (Chart prepared by W. K. Davis)

way to get fuel costs down to the competitive range of 1–2 mills/kwh is to take advantage of the savings in fissionable-material costs effected by high neutron economy. In other words utilization of excess neutrons for the production of fissionable material is necessary. This is obtained in two general types of reactors—breeders and regenerative reactors. (By the latter we mean a reactor such as the pressurized-water, boiling-water or sodium graphite reactor, in which natural or slightly enriched uranium is consumed to produce plutonium as a by-product.)

In the regenerative case, for example, if one assumes pessimistic fabrication costs and an initial conversion ratio of 0.8, a burnup of 7,000 Mwd/ton or more in a 2% enriched reactor yields a fuel cost below 2 mills/kwh. Assuming optimistic fabrication costs and an initial conversion ratio of 1.0, fuel costs of less than 1 mill/kwh are obtained for an exposure of only 3,000 Mwd/ton. For fast breeders fuel costs are extremely sensitive to the value used for Pu credit. With a Pu credit of $41.50/gm a fast breeder with a U^{235} core has an estimated fuel cost of −0.82 mill/kwh; with a Pu^{239} core the figure is +1.30 mills/kwh. For Pu at $12/gm these figures change to 4.68 and 3.56 mills/kwh respectively. Estimates for the fuel costs of an alternative kind of breeder, the large-scale homogeneous reactor, are 1.3–4.1 mills/kwh. The lower value refers to the two-region homogenous type while the higher one is for the single-region U^{235} burner type.

TABLE 2—Estimated Maximum and Minimum Nuclear Power Costs

	Minimum value	*Maximum value*
Annual Charges on Investment (%)		
Reactor plant	13	18
Turbine plant	13	15
Fuel and special materials	4	12
Load factor	90	65
Capital Costs ($/kw$_e$)		
Reactor plant	100	220
Turbine plant	95	130
Fuel inventory	30	60
D_2O inventory	30	—
Fuel Cycle Factors		
Burnup per cycle (Mwd/ton)	10,000	3,000
Fuel enrichment (% U^{235})	0.71	2.0
Plutonium credit ($/gm)	30	12
Nuclear Power Costs (mills/kwh)		
Plant investment	3.2	10.4
Fuel and D_2O	−0.5	4.5
Operating and maintenance	0.8	1.5
Total power	3.5	16.4

Total Power Costs

The trend toward higher costs noted for capital costs is, of course, also reflected in total power costs. Table 1 compares the present power-cost estimates with those made two years ago for the large-scale plants. Indications are that costs will lie in the range of 10–14 mills/kwh for these plants.

To get a feeling for the degree of uncertainty attached to future nuclear power costs, we can first set reasonable minimum and maximum values for the important factors influencing cost, such as fixed charge rates, load factor, burnup, fuel enrichment, conversion ratio and so on. Using these values we can calculate minimum and maximum values of the power cost which might be expected to serve as an indication of the uncertainty in our ability to estimate these costs. Our estimates of the minimum and maximum values for the various factors are summarized in Table 2.

It is interesting that the average power costs of the two extremes given in Table 2 are very close to 10 mills/kwh. Thus one can say that the estimated cost of nuclear power according to the 1957 data is 10 ± 6.5 mills/kwh. It is apparent that our ability to estimate nuclear power costs accurately is not great. To improve on this situation, it will be necessary to obtain actual data from reactors now being built on the extent of radiation damage to fuel elements, the growth of plutonium in fuel and changes in reactivity with time. The operation of such plants will also provide valuable information on operability, reliability, performance and longevity.

A NUCLEONICS REPORT

The Economic Situation

In connection with this special report on nuclear power costs, NUCLEONICS wrote to W. Kenneth Davis, Director, Division of Reactor Development of the U. S. Atomic Energy Commission, as follows (in part):

" . . . there is very great concern throughout the nuclear industry about what has been happening in the reactor cost picture. Little real data is available to give people the answers they're looking for . . .

"(We'd like to ask you) some questions that have arisen in our minds during the preparation of this report. Although some of these questions may be difficult to answer, it was our thought that it would be very worthwhile if we could publish your answers along with our report so that our readers might have some indication of what AEC thinking is on these perplexing issues . . . "

NUCLEONICS' questions plus Mr. Davis' answers are presented below. Mr. Davis' views about the state of the industry are perhaps best summarized by the following paragraph contained in his letter of reply:

The development of power reactors in the United States has been accompanied by two manias—insistence on detailed costs and economic analyses when no basis whatsoever has existed for such estimates and insistence on building full-scale reactors prematurely in the over-all development program. I can only hope that we are approaching a more rational period. At least we are learning more about costs and economics and are reaching a stage where the construction of full-scale prototypes of some types of reactors is indeed justified.

Q. Estimated capital costs have invariably gone up for power reactor projects as the projects mature. Do you feel these increases are peculiar to the problems of building prototypes or are there implications in this trend concerning the long range economic picture? In addition, do you see anything in the recent higher estimates that would cause you to modify your prediction in the September NUCLEONICS of competitive nuclear power in the U. S. by 1967?

In my opinion the causes of increases in capital cost estimates such as are cited include the following:

- As the question states, these are prototype reactors and, as the projects have matured, development work has usually shown necessity for changes in design, such as for more elaborate safety precautions, additional control rods and circuits, etc. Some of the estimates which have been superseded were fairly good for what was envisaged at the time they were made. They were, however, made prematurely in terms of the final design of the reactor.
- Over the period between the first and current estimates for most reactors there has been a general rise in costs of all construction amounting to about 6% a year. Some estimates now provide also for future escalation at this rate as well as for increased contingency factors.
- Three kinds of costs are involved in these early reactors, namely, research and development costs, learning costs, and actual design and construction costs. Apparent inconsistencies have been introduced because some estimates which have been published include all three items, some only the last two, and some only the third.
- And then, let's face it, there has been some plain wishful thinking and bad estimating. For example, we had before a strange situation where manufacturers claimed they could build small reactors for fewer dollars per kilowatt than they could build large ones. (As I will point out below this is no longer the case.)

But it does not seem to me to be profitable to dwell overmuch on corrections in early cost estimates which, for one reason or another, have turned out to be wrong.

We can see no basis for altering our predictions because of changes in estimates which we have known for a long time to be overly optimistic.

Q. Are the present cost estimates now really good estimates?

We have an indication that present cost estimates are approaching realism. In my October 30 talk at the Atomic Industrial Forum conference in New York, I showed a chart (reproduced on p. 47) which correlates current cost estimates per kilowatt (omitting research and development costs in all cases) with size of reactor.

This chart shows cost decreases with increasing size according to the usual way in the power industry. It indicates that current cost estimates bear at least a reasonable relationship to each other. It also, incidentally, casts doubt on the future usefulness of small reactors except under very special conditions.

Q. What is likely to be the cost of later units which will succeed the first experimental plants?

Relating to the likely costs for later units, we see several factors which can be expected to bring these down. The most important is likely to be the discovery that units now planned can produce substantially more power than their design ratings. This factor has explained almost entirely the ability of the UK to project 525 Mw(e) stations costing £110 per Mw(e) from Calder Hall units costing at least £235 per Mw(e).

In addition, various economies of scale can be anticipated from building of larger reactors or from the building of two-reactor stations, such as are being built in the UK and the USSR. As experience is gained, later generations of reactors will be simplified and cheapened, learning costs will be eliminated, and many ways to reduce costs will be found. We also anticipate that successful development of technology will lead to major decreases in fuel costs, the second large cost factor.

Q. What is the significance of these cost estimates in terms of the future of nuclear power?

Relating to the future of nuclear power, and in answer to the question about our predictions in the September, 1957 NUCLEONICS: These estimates referred to costs which might be achieved in very large nuclear power stations. They assumed success in achieving in future plants the types of cost reductions I have mentioned above. They were based also on the concept that plants would be initiated if it appeared that they would be economically competitive over their lives of 20 or 25 years even though they might not be competitive when they started operation.

As Viewed by the AEC

Q. As concluded at a recent American Nuclear Society symposium (see p. 50) in New York, a large uncertainty in the fuel cost for a slightly enriched reactor seems to be the value of Pu. (For a typical PWR design the difference between $30/gm and $12/gm means 1.3 mills/kwh.) What assurance does the reactor investor have that he will not be put out of business by future changes in government fissionable material prices?

I don't believe that the value of Pu is the greatest uncertainty in fuel costs. We have regarded fuel fabrication costs —now so high but with such potentiality for reduction—as the principal operating cost uncertainty at the present time.

No one can tell what the price of plutonium may be over the 20- or 30-year life of a reactor being planned now. The present AEC guess is that it will be worth $12/gm as a fuel for reactors when this use becomes technically and economically feasible, and the best assurance for any investor is to assume that the long term price will not exceed this value. Anyone who goes ahead with a reactor on the theory that he will get $30/gm for plutonium for weapons purposes for 20–30 years of operation has his head buried in the sand or else knows more about the future than us mortals.

If plutonium should be found to be more expensive to use as fuel than now hoped the price might not be as high as $12/gm. It might be lowered still further if the cost of U^{235}, which influences the price of other fissionable materials, went down due to lower ore processing or production costs. In this case, however, operators of most reactors would benefit more from the lower U^{235} cost than they would suffer from lower plutonium values.

Q. A general conclusion about the history of atomic energy so far might be that, compared with other industrial fields, American atomic industry has shown a marked genius for underestimating costs. Companies that are capable of very sophisticated cost estimates in allied fields have not displayed a similar talent in the nuclear field. Could you comment on what you think might be some of the basic reasons for this paradox?

Several factors can be cited to account for the parade of highly capable companies displaying such a lack of talent in estimating nuclear plant costs. The compounding of these factors resulted in considerably revised costs. Among the factors responsible the following seem to be the most important:

- Misunderstanding of costs and growth of nuclear industry. Studies had been made which indicated low cost power—of the order of 5 mills/kwh within the next two or three decades. Taking those studies out of context and exerting undue optimism led many to believe this goal was just around the corner and distorted cost estimates.
- In considering the *long term potential* many equipment manufacturers were willing to underwrite initial risks and losses and quote low prices. Many of them have had to recede from this position.
- The necessity for costly—and difficult to estimate—job-shop production of pioneering prototype equipment. Both nuclear and nonnuclear equipment requires more rigid specification than that to which the industry was accustomed and prepared to manufacture. Serious miscalculations were made about the costs of some of these equipment items.
- Slow development of the coordination of highly competent cost estimators with inadequate nuclear knowledge—with the newer group of competent but cost-wise inexperienced nuclear engineers and scientists. In my opinion this has probably been the most important reason for overly optimistic estimates.

It should also be pointed out that there have been many reasonably good cost estimates—at least for what was actually designed at the time. Not all estimates have been as bad as is implied. The combination of realistic cost estimation with better appreciation of the design requirements should result in much better cost estimates from now on.

Q. One of the conclusions of our report (see p. 47) is that the best estimates today for future nuclear power costs show an uncertainty of about 50% (10 ± 5 mills/kwh). In view of this large uncertainty, would you agree that no private investor can, as of this moment, afford to make heavy long range investments in the commercial power reactor field?

I don't quite agree with the estimated range your report gives for future nuclear power costs. I incline more to a range of $9^{+3}_{-1\frac{1}{2}}$ mills/kwh (1957 dollars, U. S. private financing) for a time which may be somewhere between 10 and 15 years ahead.

More important than whether your estimate or mine is correct is the fact that nuclear power will eventually become economic in the United States because of exhaustion of fossil fuels even though nuclear costs do not come down substantially. This, of course, is a very long time off.

The American way of doing things, however, is not to sit back and wait for nuclear power to become economic in this way, but rather to make aggressive efforts to hasten the event, thereby bringing nearer the time when nuclear power can be a profitable field of endeavor. Unfortunately the number of companies which can afford to make the continuing investments necessary to advance the art for the required length of time is not large, probably far fewer than are now in the field. However, I believe that some companies will continue in this field and that they will ultimately be successful in it.

Q. What implications does the domestic cost experience thus far have for the ability of U. S. industry to sell reactors abroad?

The actual facts about United States reactor technology and costs should make reactors developed and produced here attractive to foreign purchasers. There is a strong probability, however, that the *talk* about increases in costs in the United States, even though much of it is inaccurate and quite inapplicable to the situation of foreign purchasers, has had a damaging psychological effect which I hope will be only temporary.

A NUCLEONICS REPORT

Sizing Up Uncertainties In Nuclear Fuel Costs

A study of fuel costs for a PWR-type reactor reveals a factor-of-three uncertainty brought about principally by spread in Pu credits and fabrication charges

Who Did the Work

A panel of eight people presented the cost facts to the New York Chapter ANS Symposium reported on here. The panel was composed entirely of local talent from nuclear-minded companies in the area. Their names, affiliations and specialties read as follows:

Donald Kallman (B&W)—program chairman; Leon Davidson (NDA)—fissionable material costs; R. B. Holden (Sylvania)—fabrication costs; Robert J. Klotzbach (Union Carbide)—reprocessing costs; Clement A. Streifus (Ebasco)—shipping costs; Sidney M. Stoller (Vitro)—miscellaneous fuel costs; Felippe De la Cruz (Gibbs & Hill)—power plant efficiency; John E. Brennan (B&W)—irradiation level and summary.

Of the various factors that stand in the way of economic nuclear power, nuclear fuel costs are, by all odds, the single most important obstacle. When it has been demonstrated that nuclear plants can run at fuel costs below the national average of about 3 mills/kwh for conventional fuels, then the electric power industry will think seriously of building power reactors, even though the investment cost per kw may still be unfavorable.

At the same time, if the spread in published cost estimates can be regarded as evidence, nuclear fuel costs appear to be the least understood of any of the cost factors.

Recognizing both the importance and the present-day uncertainty of fuel costs; the New York Chapter of the American Nuclear Society recently devoted one of its regular meetings to a program designed to help clear up the fuel cost picture. Local members (see box) participated in a fuel cost symposium aimed at estimating the fuel cost spread for a conventional pressurized-water reactor. The group arrived at upper and lower limits (see table on facing page) for this figure which differed by a factor of three. The price of Pu and the fabrication cost were responsible for most of the spread between the upper and lower limits for fuel costs—the difference between crediting Pu at $30/gm and $12/gm comes to 1.3 mills/kwh.

Reference Design

The total fuel cost is a sum of a number of cost factors, the evaluation of each of which is by itself a man-size task. Thus fuel cost estimates have tended to take either of two forms: (a) the patch-work-quilt-type where several different people have worked on the several different factors, each doing a thorough job but each using different ground rules and assumptions or (b) the well-integrated but frequently shallow estimate performed by a single person or organization without the benefit of expert experience in the relevant fields.

Here the job of estimating the total fuel cost for a single standard reference design was broken down into seven different aspects, each handled by a specialist. The kind of reactor chosen was a conventional pressurized-water

Fuel Cost Breakdown for Hypothetical PWR

	Upper limit		Lower limit	
	Total cost per core (10^3)	Heat cost (¢/10^6 Btu)	Total cost per core (10^3)	Heat cost (¢/10^6 Btu)
1. Fissionable material	2,550	16.6	967	6.3
2. Fabrication	2,000	13.0	300	2.0
3. Reprocessing	460	3.0	285	1.9
4. Shipping spent fuel	220	1.4	160	1.0
5. Miscellaneous processing	1,250	8.1	408	2.7
Totals*	6,480	42.1	2,120	13.9
6. Net plant efficiency	25%		28%	
7. Irradiation level: 7,500 Mwd/ton—see Table 3 for other burnups.				

* Not included in totals is constant inventory charge of $833,000 per core or 5.4¢/10^6 Btu.

type operating at 500 Mw(th) and generating 500 psi steam. The core is loaded initially with 25,000 kg of 3%-enriched UO_2 in the form of pellets sealed in stainless steel-tubes. During operation, it is assumed 0.4 atoms of Pu were created for every atom of U^{235} destroyed by fission or capture. The core is removed when 220 kg of U^{235} has been burned, thus reducing the enrichment to 2%. An 80% plant factor was assumed in cost calculations.

The problem was to calculate upper and lower limits for each part of the fuel cost assuming the plant were to be put in operation in 1962. In making these calculations no credit was taken for possible future technical advances.

Fissionable Material Costs

In calculating the costs of the use and burnup of fissionable material it was further assumed that 0.18 U^{235} atoms were destroyed by radiative capture for every U^{235} atom fissioned and that each core loading is left in the reactor for its full life without any shuffling or partial reloading.

After making allowances for 1% losses during the conversion of UF_6 to UO_2 and the reprocessing of the spent fuel, the AEC's official schedule of charges for enriched uranium gives the following figures for the net fissionable material cost per core loading:

Value of 22,220 kg U borrowed (3% U^{235})	$8,333,000
Credit for 21,480 kg U returned from reprocessing plant (2% U^{235})	4,726,000
Loss in value due to loss in quality and quantity of uranium	3,607,000
Maximum Pu credit @ $30/gm	−2,640,000
Minimum net cost	$ 967,000
Minimum Pu credit @ $12/gm	−1,057,000
Maximum net cost	$2,550,000

Since the AEC does not sell but merely leases enriched uranium to domestic users, a "use charge" must be added to the above expenses.

The current figure for this use charge in the U. S. is 4%, but this can vary here if interest rates change appreciably and will probably be different in other countries.

The charge applies from the time the material first leaves the diffusion cascade until the used fuel is reprocessed and returned to government custody. The charge is presumably based on the full value of the amount originally drawn from the cascade as accounts will probably be settled after a core has been reprocessed.

An estimate of the time during which "use charges" apply is:

Item	Time (months)
Time for fuel preparation from UF_6	3
Time in spare fuel inventory at reactor site	6
Time for cooling after discharge	4
Time in transit, reprocessing, etc.	3
	16
Residence time in reactor core	16
Cumulative total	32

$$\text{Use charge} = 4\% \times \frac{32}{12} \cong 10\%$$

Since the initial uranium "purchase" value is $8,333,000 then the cumulative use charge for one core loading over its whole history will be $833,000.

Fabrication Costs

The over-riding factor in fuel fabrication cost is the extent to which close tolerances are specified in the fuel element design. To present a fair picture, the fabrication-cost estimates were based on the following set of design specifications considered to be reasonable both from the manufactuer's and reactor designer's point of view:

UO_2 pellet:

Diameter	0.346 ± 0.002 in. as fired
Length	0.346 ± 0.005 in.
Density	95% of theoretical density or 10.4 gm/cm³
Weight	5.55 gm/pellet
Number required	$\frac{25 \times 10^6 \text{ gm/core}}{5.55 \text{ gm/pellet}} = 4.5 \times 10^6 \frac{\text{pellets}}{\text{core}}$

Fuel rod:

Diameter	0.400 in.
Active length	6 ft (~)
Pellets per rod	208
Rods per bundle	64
Bundles per core	338

The following operations would be performed in manufacturing elements for the hypothetical reactor:

Preparation of UO_2-granulation
Pellet pressing, firing, inspection
Loading of pellets into stainless tubes
Welding end plugs into loaded tube
Leak testing of fuel rods
Bundle assembly
Final inspection

For a first core, the operations above may require about 15% additional nuclear material because of rejects and off-specification pellets, rods or bundles. For later cores this requirement might be reduced to about 5%.

The total cost of manufacturing a core for the first time to the specifications above would cost between $675,000 and $1,300,000. To produce this core according to the more stringent specifications frequently set would cost perhaps $2,000,000.*

As fuel-element fabrication becomes a volume business, a plant producing ten cores per year could conceivably turn out cores to the assumed specifications for $300,000 per core.

Reprocessing Cost

Data on reprocessing costs available so far is entirely speculative, referring to hypothetical processes in hypothetical plants. Perhaps the firmest of these is the "Multipurpose Chemical Processing Plant" proposed by the AEC in March, 1957 (NU May '57, p. 17). The plant consists of a tailend Purex system rated at 1 ton/day natural- or slightly-enriched U and headend systems (e.g., Darex) designed to handle a variety of fuels. The AEC estimates a building cost of $20,570,000 and an annual operating cost, including waste disposal, amortization and allowance for AEC overhead and other intangible expenses, of $4,592,000. On this basis the daily charge to a private customer using the plant would be $15,300. The time charged for includes that required to process the core in the solvent extraction tailend, plus the time required for startup, shutdown and cleanup of the processing system.

The reference-design core would take 22 days to reprocess and an additional 8 days for plant startup, shutdown and cleanup in the hypothetical AEC plant. This amounts to a processing charge of $460,000.

Although this is a charge at which the AEC is willing to negotiate a firm contract, the hypothetical plant upon which the charges are based is a highly subsidized operation. The plant would, for instance, be built on a government site and have the advantage of many government services and facilities. To arrive at a realistic reprocessing charge one must consider a privately owned and operated plant.

If one considers the cost to a company of the extra services provided the government plant and adds in a reasonable contingency factor, the capital investment required may be $28,000,000 rather than $20,570,000. Similarly the annual operating cost would go up to $5,300,000 exclusive of normal profit and income tax charges. Allowing a minimum return on the investment gives a processing charge for the reference core in a 1-ton/day privately-financed multipurpose plant of $36,600 per day or a total charge of $1,100,000. This assumes the plant has enough business to operate at full capacity. However, there is not enough fuel available, even including the AEC's base load quantities to operate the plant at 100% capacity at the present time. Estimates of the current market show that less than 50% of the plant's capacity might be used initially which would give a processing charge of over $2,500,000 per core.

On the other hand, if, eventually, larger plants processing 10 ton/day are built, the costs would be lower. If the plant was government owned and operated, the core could be reprocessed for $285,000. If private industry was to operate this larger reprocessing plant at 100% load factor with allowances for profit, the cost might be $365,000 per reference core.

TABLE 2—Charges for Auxiliary Processes

	Maximum		*Minimum*	
Process	*Rate ($/kg)*	*Charge ($/core)*	*Rate ($/kg)*	*Charge ($/core)*
UF_6 to UO_2	30	750,000	10	250,000
UNH to UF_6	12	280,000	3	66,000
PuNH to metal	2,400	220,000	1,000	92,000
Subtotal		1,250,000		408,000

Shipping Costs

Although shipping of spent fuel is not a major item of expense, an attempt was made to evaluate the size of this cost and determine the most economical method. The problems in general are economic, physical and regulatory.

Taking into account such things as truck and railroad capacities and rates, terminal handling equipment, AEC and insurance regulations, personnel shielding requirements, and enroute cooling needs, one arrives at a rough figure for the ratio of the cask weight to spent fuel weight required to do the job. Conservative estimates show that transporting the fuel obtained from the design reactor to the reprocessing plant would require a cask that weighs 40 lb per lb of uranium shipped. If the distance between the power plant and the reprocessing installation is taken to be 2,000 miles, the freight bill for the whole core would be about $220,000. It is likely that shipping fuel in larger containers will reduce the weight ratio to 30 lb or even 20 lb per lb of uranium. The total freight would then fall in proportion.

Other Fuel Costs

Up to this point there are a number of gaps in the fuel-expense picture. The more important of these expenses are considered in detail here; there are, however, a number of other very small additional expenses which add up to a total miscellaneous expense of perhaps $100,000 per core.

The major "other fuel expense" is

* It should be noted that to date no one has fabricated elements of the type under discussion for a cost as low as the upper limit of $2 million.

Why Leave Out Inventory Charges?

In reporting their results the panel excluded in-pile (but not out-of-pile) inventory charges from the fuel cost. They reasoned that the in-pile cost is independent of plant use and is therefore a fixed rather than an operating expense. The analogous practice is followed in conventional-power-plant book keeping where central coal inventory expenses are charged against fixed costs. Thus in comparing nuclear fuel costs with conventional fuel costs the in-pile inventory charge is properly excluded.

the charge for converting UF_6 to UO_2. Quotations are available for the performance of this service and these average about $30/kg for 3%-enriched uranium. As UO_2 requirements and thus plant throughput increase this cost will decrease. We have estimated that a hypothetical plant would be capable of converting 3%-enriched UF_6 to UO_2 at about $20/kg.*

After spent fuel is reprocessed it will be in the nitrate form. If it is desired to re-enrich the spent 2%-enriched uranyl nitrate (instead of blending in some new highly enriched uranium or plutonium) the cost of converting to the hexafluoride form would cost $12/kg in a small plant. In Euratom report a footnote indicates a cost of about $3/kg may be assumed for large-scale operation.

One other charge to be considered is the expense of converting plutonyl nitrate to the metal button form specified by the AEC as an acceptable form. Due to the very low volume of plant throughput anticipated in the near future for this conversion process, estimates indicate that costs could run as high as $2.40/gm. The U. S. AEC recommends an allowance of $1.50/gm for this cost. Large volume plants in the future could conceivably perform this processing for $1.00 or perhaps even $0.50/gm. This very expensive low-volume conversion to Pu may never be practiced commercially if it proves to be cheaper to blend the recovered material (after a simpler conversion to oxide) with slightly enriched uranium for subsequent core loadings.

Table 2 summarizes the maximum and minimum rates presented for the services discussed along with the charges applicable to the reference core.

Plant Efficiency

Net plant efficiency enters into fuel cost since it determines the amount of fuel that must be burned to produce a unit of electrical energy. For the steam conditions specified, the net efficiency is largely a function of the feedwater heater arrangement. Thus, if the condensate leaving the condenser is pumped directly to the steam generator with no intervening heat exchange equipment, the water must be heated from say 90° F up to H.P. saturation temperature before evaporation can take place. For the 500-psia cycle under discussion, thermal efficiency is about 25%.

By adding three feedwater heaters to the cycle, and extracting steam from three points along the turbine steam path, the condensate can be heated to say 330° F on the way back to the steam generator. Thermal efficiency is increased to about 28%. Note that this represents an increase of 12% in thermal efficiency with a decrease in fuel cost proportional to this 12% increase. For any given steam conditions an optimum number of feedwater heaters can be determined. The number of heaters thus varies from say three in the 500-lb cycle under consideration to 7 or 8 heaters in the 2,500-lb cycle used in modern plants.

Cost Summary

The maximum and minimum values for the various cost factors discussed so far are tabulated in Table 1 in terms of total cost per core and in cents per Btu. The fissionable material cost, since it is based on official AEC price schedules is quite accurately determined. The high and low values are derived by assuming a Pu-buy-back price of $12/gm and $30/gm respectively.

The table shows fabrication cost to be the least certain factor, having a spread of 7 to 1. Some fabricators would question even these limits. Reprocessing and shipping are more accurately known and should stay within the fairly narrow range indicated. "Other fuel expenses," like fabrication, has a fairly wide expense range.

TABLE 3—Fuel Cost as a Function of Burnup

Irradiation level (Mwd/ton)	*Upper limit* (mills/kwh)*	*Lower limit* (mills/kwh)*
5,000	7.9	2.6
7,500†	6.2	2.0
10,000	5.2	1.8
15,000	4.3	1.5
20,000	3.8	1.3
25,000	3.5	1.2

* Does not include in-pile fuel inventory charge.
† Reference design point.

The total cost in mills/kwh can be had by multiplying subtotals in the table on p. 51 by the heat rate in each column. This gives a maximum value of 6.2 mills/kwh and a minimum of 2.0 mills/kwh. Not included in either of these figures is a 0.35-mill/kwh in-pile inventory charge (see box). The burnup parameters assumed in deriving these figures imply a fuel irradiation exposure of 7,500 Mwd/ton. The fuel cost was calculated for other irradiation levels by assuming that, except for fissionable material cost, the cost factors are inversely proportionally to burnup. The results are shown in Table 3. The in-pile inventory charge, which is not included in the table, increases with higher burnup since more highly enriched fuel is used. The out-of-pile inventory charge, which *is* included in the fuel cost, decreases with burnup. For the burnup range 5,000 to 25,000 Mwd/ton, the former goes from 0.30 to 0.70 mills/kwh and the latter from 0.40 to 0.20 mills/kwh.

At all levels one sees that the uncertainty in fuel cost is roughly a factor of three. The national average fuel cost of 2.7 mills/kwh for coal-fired plants is at least bracketed by the two columns for each of the burnups considered. It is interesting to note that the difference in Pu credit causes a constant difference of 1.3 mills/kwh between the high and low values. Thus if one were optimistic about everything except the price of Pu (see p. 48), which is equivalent to adding 1.3 mills/kwh to the low value column, then the fuel cost would not be competitive until burnups of 15,000 Mwd/ton were achieved.

* Information that presents costs lower than $20/kg of UO_2 can be found in TID-7158. It is estimated from this source that 3%-enriched uranium can be converted for $10/kg.

A NUCLEONICS REPORT

Pricing Enriched Uranium

An analysis of separation-plant economics yields the published U price scale, explains how to calculate equivalent amounts of U at different enrichment and leads to a simple method for estimating reactor fuel burnup cost

By HAL L. HOLLISTER* and ARTHA JEAN BURINGTON
Office of Operations Analysis and Planning, U. S. Atomic Energy Commission, Washington, D. C.

EDITOR'S NOTE: *The price of uranium is, at the moment, one of the most important factors entering into nuclear fuel costs. As experience acts to lower the costs of fabrication and reprocessing and increased burnups become possible, the cost of the fissionable material itself will become, relatively speaking, even more important. Conceivably the time may come when nuclear fuel costs can be calculated by making reference only to published price scales. These facts naturally lead to curiosity about the factors influencing the official uranium price scale. The following article should do much to satisfy this curiosity.*

A PRICE SCALE for the sale or lease of enriched uranium was announced by the AEC in November, 1956. We would like to show here how a price scale that agrees with the published scale can be derived from elementary considerations of isotope-separation economics (Fig. 1). In addition to providing insight into the basis of the price scale, these considerations help in understanding what amounts of uranium at different enrichments are "equivalent" and yield a simple scheme for estimating the cost of U^{235} burnup in a reactor.

Ideal Cascade Theory

There is a considerable body of unclassified technical literature on isotope separation, particularly on ideal cascades of isotope-separation stages (*1–3*). We will review here some of the concepts of ideal cascade theory that will be important to our later discussion. An ideal cascade is defined as a stagewise arrangement for isotope separation in which for each stage the downflow from the stage above and the upflow from the stage below have the same isotopic enrichment.

Figure 1 shows a simplified schematic flow diagram for a separation-plant cascade. F denotes the input weight flow of feed material with U^{235} concentration† x_F; P is the flow of the enriched product from the top of the cascade at assay x_P and W is the flow of depleted waste material from the bottom of the cascade at assay x_W. Assuming steady state we can write two material balances for total U and for U^{235}

$$F = P + W \qquad (1)$$

$$Fx_F = Px_P + Wx_W \qquad (2)$$

In general the operation of a cascade requires energy input in the form of pumping power to provide the interstage flow. The total flow and the stage separation factor define a quantity called the separative work rate. For an ideal cascade the separative work rate Δ is related to the material flow rates by

$$\Delta = PV_P + WV_W - FV_F \qquad (3)$$

where Δ is expressed in units of flow and V_i, the separation potential for stream i, is $V_i = (2x_i - 1) \ln (x_i/1 - x_i)$.

Equations 1–3 can be generalized to apply to an ideal cascade having any number of feed and product streams. In general the separative work performed by the cascade is the difference between the separative work content (i.e., stream flow times separation potential) of the product streams and the feed streams.

The major costs that are involved in producing material at some enrichment x_P are (a) the cost of the feed material and (b) the cost of the separative work (plant-amortization and operating costs can both be included as part of the latter). If C_F is the cost per unit of feed material and C_Δ is the cost per unit of separative work then, assuming the waste material in stream W has no economic value, the cost of a unit of enriched material C_P is

$$C_P P = C_F F + C\Delta \qquad (4)$$

By substituting Eqs. 1, 2 and 3 in Eq. 4 it is possible to derive an expres-

* PRESENT ADDRESS: Staff, Division of Biology and Medicine, U. S. AEC, Washington, D. C.

† "Enrichment," used interchangeably with "concentration" and "assay," is defined here as the weight fraction of U^{235} contained in a mixture of U^{235} and U^{238}.

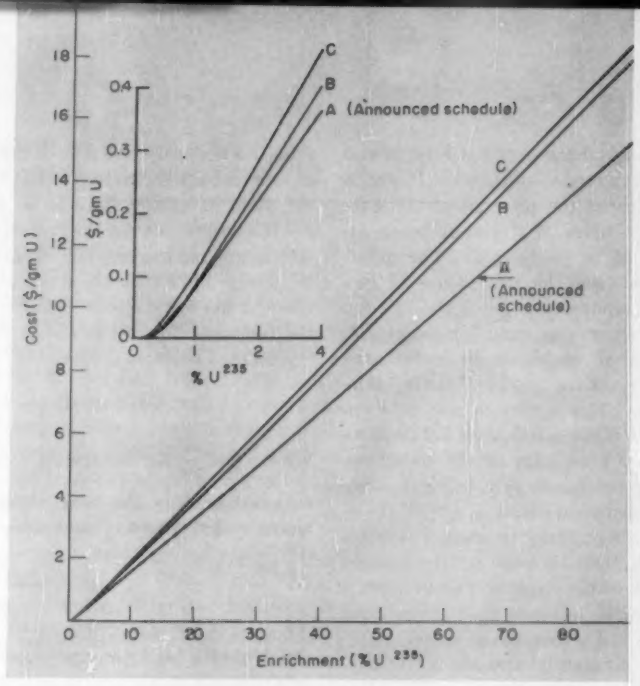


FIG. 1. Uranium price curves calculated using ideal cascade theory. Curve A, which agrees with official AEC scale, assumes C_F = \$39.27/kg and C_Δ = \$37.29/kg. For Curve B, C_Δ was changed to \$50/kg; for Curve C, C_F was changed to \$50/kg

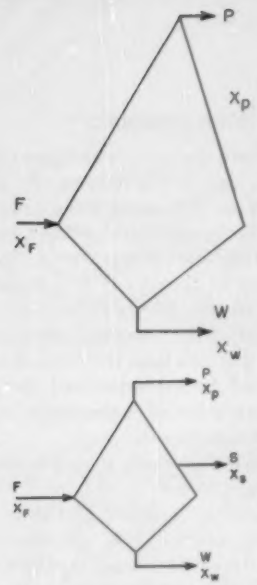


FIG. 2. Isotope separation plant flow diagrams: (top) single product plant and (bottom) plant with sidestream product

sion for the product cost that is independent of P, F and Δ and is a function only of the cost of feed material and separative work and the enrichments of the three streams

$$C_P = C_F\left(\frac{x_P - x_W}{x_F - x_W}\right) + C_\Delta\left[V_P + \left(\frac{x_P - x_F}{x_F - x_W}\right)V_W - \left(\frac{x_P - x_W}{x_F - x_W}\right)V_F\right] \quad (5)$$

Returning to Eqs. 1 and 2, we note that there are three assays and three stream flows or six variables. The feed assay and flow and the product assay are ordinarily given. If then a value for the waste assay is chosen, the product and waste flows are determined by Eqs. 1 and 2. It is desirable to set the waste-stream assay at a value that will make the unit cost of the wanted product a minimum. By taking the derivative $\frac{dC_P}{dx_W}$ of Eq. 5 and setting it equal to zero, we find that for minimum product unit cost, the waste stream assay x_W must be equal to the value given implicitly by

$$\frac{C_F}{C_\Delta} = V_F - V_W - (x_F - x_W)V_W' \quad (6)$$

where

$$V_W' = \left(\frac{dV(x)}{dx}\right)_{x=x_W}$$

It is worth noting that the waste assay for minimum product cost (a) is independent of product assay and (b) depends only on the assay of feed and the ratio of the feed and separative work costs.

The minimum product cost itself is found by substituting Eq. 6 into Eq. 5 (making the substitution for C_F because of the awkwardness of getting x_W explicitly)

$$C_P = C_\Delta[V_P - V_W - (x_P - x_W)V_W'] \quad (7)$$

Equation 6 is known as the zero-cost tails equation. Equation 7 is called the theoretical-price (cost would be more accurate) equation since it gives the optimum cost of producing a product of specified enrichment.

Figure 1 shows three price scales, illustrating the effect of assuming different values of C_F and C_Δ, and including one which agrees with the recently announced scale for domestic and foreign use. The announced schedule was matched by using the costs, C_F = \$39.27 per kg of uranium and C_Δ = \$37.29 per kg of separative work, which imply according to Eq. 6 a zero-cost assay of approximately 0.221%.

Some sample calculations for the theoretical cost schedule which match the AEC announced prices for uranium in the form of UF_6 are shown in the table.*

(Continued on next page)

Diffusion-Plant Economics

Virtually all enriched uranium in the United States is produced by the gaseous diffusion process. Excellent discussions of the basic principles of uranium isotope separation by this process are available in standard texts (1–3). The process operates on the principle that, under the same driving pressure, a gas of lower molecular weight will diffuse more quickly through a porous barrier than will a gas of higher molecular weight. Specifically the diffusion goes inversely as the square root of the molecular weight. Thus if about half of a certain amount of uranium hexa-fluoride is allowed to diffuse through a porous barrier, compared with the gas that is left behind, the gas which passes the barrier will be richer in U^{235} by the factor

$$\left(\frac{238 + 6 \times 19}{235 + 6 \times 19}\right)^{1/2} = \left(\frac{352}{348}\right)^{1/2} = 1.0043$$

Since the enrichment thus provided by a single diffusion stage is quite small, it is necessary to make use of the order of thousands of stages in a cascade arrangement to provide final enrichments as high as 90%.

—The Editors.

* If linear interpolation is used to find the cost of assays intermediate between the officially published price assays, such interpolation should, as can readily be verified, be on a \$/gm of U basis, not \$/gm of U^{235}.

Sidestream Economics

We have derived the published price scale by calculating the cost of a given enrichment of U under the assumption that it is the sole useful product from a separation plant of the type in Fig. 2a. This can be thought of as a simplified model of the AEC's diffusion plant. However, when enriched uranium of some assay less than the product assay is needed for an authorized user, the AEC can draw off a sidestream of the desired enrichment.

It is not obvious that the cost of material produced in this way will be the same as that calculated by the methods above. We will show that this is the case provided the sidestream is small compared with the main product stream.

We can think of a plant with one feed and three rather than two product streams, as shown in Fig. 2b. The third stream of flow rate S and assay x_S is small compared with either P or W. In this situation, stream P is called the "top"-product stream.

To find the value of the material in S we would like to know how much flow in sidestream S corresponds to a given decrease in flow for top-product stream P. The value of the material in S is then just equal to the value of the material lost in stream P.

The rigorously correct way of answering this is to write material balances around the plants of Figs. 2a and b and determine the values of Px_P with and without the presence of the sidestream, values of F and Δ being assumed to be unchanged. The difference between the two values of Px_P thus computed represents the lost top product resulting from the sidestream withdrawal and can be called the "equivalent top product" of the sidestream. This approach not only involves tedious calculations but requires an exact knowledge of the actual operating conditions of a particular isotope separation plant.

If, as is generally the case, we assume the sidestream is quite small compared with the other streams, we can apply a differential analysis that gives good results and is easy to calculate.

The differential-analysis method requires an assumption that operating conditions of the plant are approximated by the conditions leading to the theoretical price schedule but does not involve a knowledge of these conditions. Let us write the separative work rate and material balances for the plant of Fig. 2b, an ideal cascade with both a sidestream and a top-product stream

$$F = P + W + S \tag{1a}$$

$$Fx_F = Px_P + Wx_W + Sx_S \tag{2a}$$

$$\Delta = PV_P + WV_W + SV_S - FV_F \tag{3a}$$

Consider the assay and flow of the feed stream and the separative work rate of the plant at steady state to be fixed. Let the assays, but not the flows, of the sidestream and top product stream also be fixed. If neither the flow nor the assay of the waste stream is fixed, then the system of Eqs. 1a, 2a and 3a can be represented functionally as

$$P = f(S, x_W, W)$$

We can find $\frac{\partial P}{\partial S}$ for this system by differentiating each of the three equations above with respect to S and solving for $\frac{\partial P}{\partial S}$ getting

$$\frac{\partial P}{\partial S} = -\frac{V_S - V_W - (x_S - x_W)V_W'}{V_P - V_W - (x_P - x_W)V_W'} \tag{8}$$

The negative sign indicates that withdrawal of sidestream results in *loss* of top product.

Now, provided the sidestream is small, we can use the derivative just determined to approximate the ratio of top-product loss to sidestream flow. That is

$$\frac{\delta P}{S} \approx \frac{\partial P}{\partial S}$$

Furthermore, comparison with Eq. 7 shows that the right-hand side of Eq. 8 is just equal to the ratio C_S/C_P where these are the product costs as calculated using the scheme of Fig. 2a. Thus

$$\frac{\delta P}{S} \approx \frac{C_S}{C_P} \quad \text{or} \quad SC_S \approx \delta PC_P$$

That is, the total cost of the material in the sidestream is approximately equal to the total cost of the material sacrificed from the top product stream of the cascade. Thus we have shown that, within the approximations indicated, it is justified to use the simple analysis based on Fig. 2a to calculate the value of U at any given enrichment.

In practice then the theoretical price scale in Fig. 1 can be used to compute the amount of side-stream U equivalent to a certain amount of the top product. For example, from the price scale one sees that 1 kg of U^{235} at 90% assay costs the same as 2.26 kg of U^{235} at 1% assay. Thus, 1,000 kg of U^{235} at 90% is equivalent to 226,000 kg of U at 1% enrichment.

The same analysis applies to a case

Sample Calculations for Fuel Price Curves

Concentration of product x_p (% U^{235})	*Separation potential* V_p	*Ratio of product cost to separative work cost* $\frac{C_p}{C_\Delta}$	*Theoretical price scale* C_p ($/kg U)	*Range of burnout costs*		*Equivalent top product conversion ratio* $\frac{C_p}{x_p} \Big/ \frac{C_{90\%}}{90\%}$
				lower bound $\frac{C_p}{x_p}$ ($/gm U^{235})	*upper bound* $\frac{dC_p}{dx_p}$ ($/gm U^{235})	
0.221	6.08553	0	0	0	0	0
0.4	5.47331	0.21782	8.12	2.03	7.59	0.119
0.6	5.04866	0.72060	26.87	4.48	10.73	0.262
0.7115	4.86813	1.05712	39.42	5.54	11.72	0.324
0.8	4.74316	1.34252	50.06	6.26	12.31	0.367
1.0	4.50322	2.03001	75.69	7.57	13.26	0.443
2.0	3.73615	5.90006	219.99	11.00	15.17	0.644
5.0	2.65000	18.72527	698.19	13.96	16.36	0.818
10	1.75778	41.01865	1,529.42	15.29	16.80	0.896
20	0.83178	86.46385	3,223.89	16.12	17.05	0.944
50	0	224.74567	8,379.87	16.76	17.29	0.982
90	1.75778	411.98825	15,361.39	17.07	17.78	1.000

in which the sidestream is fed to the diffusion plant rather than withdrawn from it. This would be the case when an authorized user of enriched uranium returned some to the AEC; for example, a reactor operator might return uranium recovered from his spent fuel elements. Then the effect on the top-product stream would be positive, that is, the additional feed would result in an increase in top product. In such a case the effect on top product, or equivalent top product, may be also referred to as the incremental productivity of the feed sidestream, and can be approximated by a marginal productivity analysis following the same argument as given above.

If additional feed for the diffusion plant is readily available, it may be possible to withdraw a sidestream from the diffusion plant keeping constant the tails concentration instead of the feed as assumed heretofore. In this case it is possible to derive a useful expression for equivalent top product valid for any size sidestream (provided, of course, there is sufficient separative work to produce the sidestream).

In making these calculations the quantity $C_S x_P / C_P x_S$ is always required. For convenience this quantity has been plotted as a function of x_S in Fig. 3.

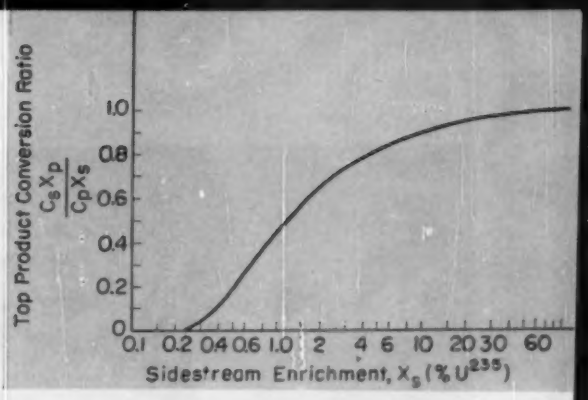


FIG. 3. Equivalent-top-product conversion ratio as a function of fuel enrichment (top product assay = 90%)

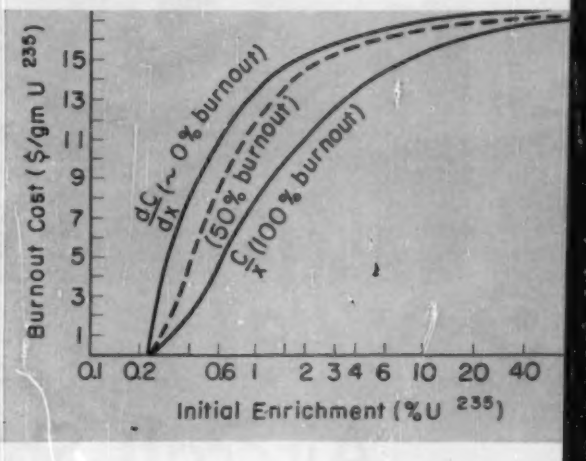


FIG. 4. Upper and lower bounds for fuel-burnout costs as a function of initial enrichment of U

Burnup Cost

The price table can also be used to calculate the cost of the U^{235} burned out during a fuel cycle. This can be found directly by taking the difference between the total cost of the uranium fed to the reactor per cycle and the cost of the uranium discharged from the reactor per cycle. The cost per gram of U^{235} burned out (exclusive of reprocessing changes) is

$$\frac{\Delta C}{\Delta x} = \frac{C_1 m_1 - C_2 m_2}{m_1 x_1 - m_2 x_2}$$

where: x is the assay of the material
m is the weight of uranium (not just U^{235})
C is the price of the uranium at the specified assay
subscript 1 refers to material fed to the reactor
subscript 2 refers to material discharged from the reactor.

It is worth noting two convenient upper and lower bounds for what the burnout cost can be.

It can be shown that when the amount of uranium burned out is very small, an upper bound for the above expression is dC/dx.

This derivative can be found by differentiating Eq. 7, and getting

$$\frac{dC}{dx} = C_\Delta [V'(x) - V'(x_W)]$$

A lower bound occurs when all of the U^{235} is burned out, i.e. when $x_2 \to 0$ and $C_2 \to 0$ (assuming a theoretical price scale of the sort developed earlier where C approaches zero as x approaches zero). The limit of the above expression then is C_1/x_1.

(It can be noted that, since $C(x)$ is convex, and since $C(x) = 0$ for some $x > 0$ we have

$$\frac{dC}{dx} > \frac{\Delta C}{\Delta x} > \frac{C}{x}$$

Thus $\frac{dC}{dx}$ and $\frac{C}{x}$ form upper and lower bounds respectively for the cost of U^{235} burned out in a reactor.)

Many practical cases of burnout cost, including all cases where the fuel is slightly enriched and the fractional burnout of U^{235} is less than about 20%, will fall sufficiently near the upper bound so that $\frac{dC}{dx}$ serves as a good approximation.* (See Fig. 4.)

* * *

This report is based upon material that was developed over a period of years from the theory of ideal cascades for isotope separation primarily by members of the Office of Operations Analysis and Planning, U. S. Atomic Energy Commission; M. Benedict, A. J. Burington, A. V. Butterworth, L. Davidson, D. P. Herron, H. L. Hollister and F. B. Quackenboss. Additional contributions were made by G. Garrett, Carbide and Carbon Chemicals Company.

The dissemination of this information is not intended to imply that these methods are necessarily those which will be used by the Atomic Energy Commission.

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* The use of $\frac{dC}{dx}$ as an approximation for the cost of U^{235} burned out in many practical reactor cases was suggested by W. K. Davis, Division of Reactor Development, USAEC.

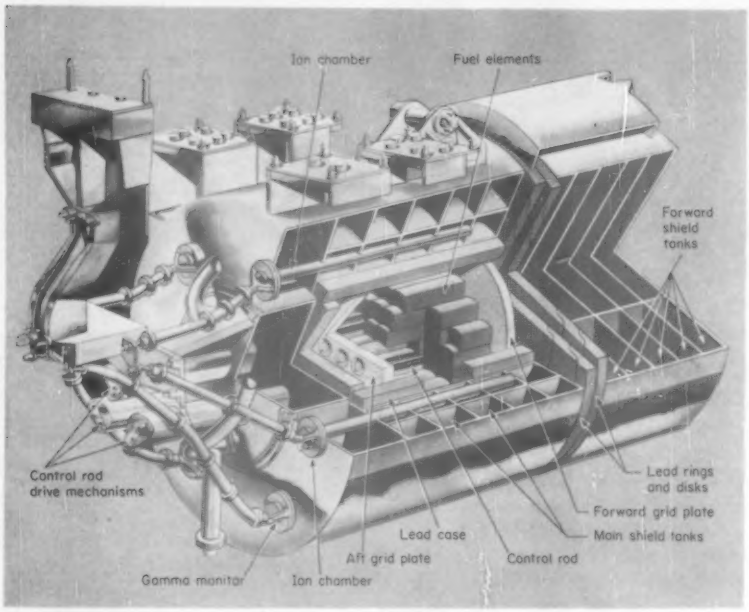


FIG. 1. ASTR (in cutaway view) has following characteristics:

Power output (heat)	1,000 kw
Thermal neutron flux	
—avg	6.3×10^{12}
—max	1.2×10^{13}
Fuel element	
—type	plate
—composition	U-Al
—cladding	Al
Fuel loading	4,800 gm highly enriched U
Core configuration	right cylinder
Control rods	
—number	3
—composition	cadmium-lined steel
—worth	$2.00 each shim, safety; $0.25 regulating
Coolant/moderator	
—type	light water
—flow	500 gpm

Aircraft Shield Test Reactor

Although not a propulsion reactor, ASTR has advanced nuclear-propelled flight. Designed to provide aircraft shielding data, it has helped solve other problems—particularly reactor handling

By J. C. NANCE and L. W. PERRY
Convair Division, General Dynamics Corp., Fort Worth, Texas

A NUCLEAR REACTOR went critical while airborne for the first time ever on September 5, 1955. This milestone marked the culmination of three years of reactor engineering and development by the Convair–Fort Worth Division of General Dynamics working as part of the U. S. Air Force's Aircraft Nuclear Propulsion effort.

In the fall of 1952 a decision was made to build an airborne test reactor to serve as a radiation source for supplying shielding information not obtainable at ground facilities. The following general specifications were established for the Aircraft Shield Test Reactor (ASTR):

- 1,000 kw of thermal power
- Size and weight restricted to enable high-altitude flight in a B-36
- Changes in shield configuration to be performed remotely while in flight
- Reliable performance of all systems under extreme environmental conditions of temperature, humidity, pressure, vibration and shock
- Reactor systems to be capable of completely remote assembly, disassembly, maintenance, ground transport and loading.

Design Problems

By March, 1953, the preliminary design of the ASTR was completed and efforts turned toward detail design and development. Several major developmental problems required extensive effort.

Control rod and drive mechanism. A light-weight, horizontally mounted control rod and control-rod drive mechanism were required to operate underwater through a pressure-vessel seal. This system had to operate satisfactorily under vibration and shock, yet be positive acting for scramming.

Reactor instrumentation. A complete nuclear detecting, amplifying, controlling and recording system had to be developed of miniature, lightweight and rugged construction that would perform adequately under conditions of extreme vibration, shock, temperature and pressure. The entire system had to be coupled and decoupled to the reactor remotely.

Cooling system. A 1,000-kw water-to-air heat exchanger of very light weight was needed. The system had to be compatible with available aircraft electrical power sources. Further, it had to be positively and remotely coupled and decoupled with minimum spillage of coolant or shielding solution.

Remote-handling equipment. The entire system had to be capable of remote handling for disassembly, maintenance, assembly, movement to outdoor test locations and to the aircraft loading pit as well as for loading into the aircraft for flights. Systems had to be developed to enable remote attachment of all hydraulic, electrical and mechanical support structures to the aircraft.

By October, 1953, the design was essentially completed. In September 1954, the assembly of fully tested reactor hardware began. Preoperational system proof testing accompanied each step. By mid-November assembly was complete and criticality was first achieved on November 27, 1954.

Summary Description

The ASTR core consists of an array of 34 highly-enriched-uranium plate-type fuel elements horizontally mounted between two grid plates. The fuel elements are similar to the familiar MTR type; however, considerable modifications were necessary to enable horizontal mounting, to insure resistance to vibration and shock, and to provide for operation at any attitude. Demineralized water, flowing at 500 gpm in a two-pass system, serves as moderator, reflector and coolant. Figure 1 shows the fuel-element arrangement and other salient features of the ASTR.

Reactivity control is achieved by three spring-loaded, cadmium-lined, stainless-steel rods that enter the core horizontally through the aft face. Each rod is withdrawn from the core by a drive motor through a gear system.

The two centrally located rods provide safety and shim control while a peripheral rod is used for regulation. The rods are physically identical, but the control rods differ in effectiveness because of their differing location in the core. Fig. 2 shows a rod, mechanism and actuator motor.

The shielding arrangement, shown in Fig. 1, allows wide flexibility for the airborne shield-test program. Any of nine shield tanks can be drained or filled remotely (on the ground or airborne) with aqueous solutions. The forward shadow-shield assemblies, composed of two disks and four rings, can be installed or removed during reactor maintenance periods in the handling tank. These assemblies can be filled with air, lead or aqueous solutions. All told, 26 significantly different shielding configurations can be obtained by suitable combinations of filled and empty shield tanks.

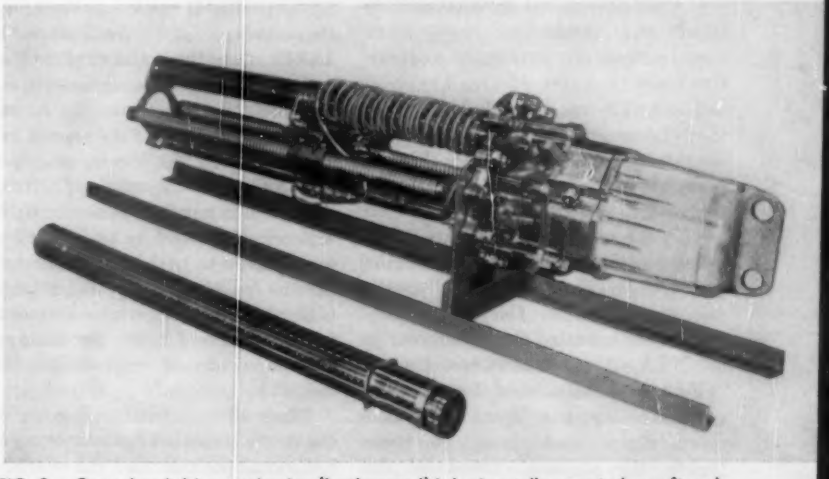


FIG. 2. Control-rod drive mechanism (background) is horizontally mounted on aft end of ASTR. Electric motor drives lead screw and nut to impart motion to electromagnet to move cadmium-lined control rod (foreground)

Cooling System

The reactor cooling systems, ground and airborne, are designed to maintain the ASTR at an average operating temperature of 150° F (inlet 140° F, outlet 160° F) at the maximum power level of 1,000 kw. When the reactor is operating on the ground, a 500-gpm circulating-water cooling system, including a water-to-water heat exchanger, is used. The reactor coolant temperature can be maintained by an automatic servo system at any desired temperature from ambient to 200° F.

For airborne reactor operations, a water-to-air cooling system is provided in the airplane that allows sustained operation at maximum reactor power.

Ground and Flight Testing

The three months following initial criticality were devoted mainly to determination of the nuclear characteristics and parameters of the reactor core. Systematic measurements were made of critical masses, flux and power distributions, control-rod effectiveness, temperature and power coefficients,* core void coefficients, fuel-plate temperatures, and dynamic control system responses. During this time nuclear and thermal power calibrations of the reactor instrumentation were also performed.

The ASTR was designed and built on the basis of nuclear calculations alone, without benefit of critical-experiment facilities. The minor changes in the reactor system, indicated as desir-

* J. C. Nance. Temperature coefficient of aircraft shield test reactor, NUCLEONICS **14**, No. 8, 98 (1956).

able by the posteritical testing, were made rapidly, and, by April of 1955, the reactor was ready to begin ground tests in conjunction with a modified B-36 (called the Nuclear Test Airplane or NTA).

The ASTR posteritical testing had been accomplished in such a way that the reactor residual radiation was held to a minimum. This allowed personnel access about the reactor for the subsequent ground tests. During these tests, the ASTR ground-handling equipment was checked and rechecked in actual operation. The complex operation of loading the ASTR into the NTA was cycled many times to ensure that the remotely-coupled hydraulic, electrical and mechanical connections would successfully operate on a repetitive basis.

The ASTR was remotely loaded into the NTA and operated by means of the aircraft control system with the airplane in a static condition. Next, with the reactor shut down, all engines on the NTA were run-up on the ground to determine the effect of vibration on the complete ASTR system. Finally, with minor revisions to the system, the ASTR was operated at a low power in the NTA with all engines operating.

Following the successful completion of these ground tests, a series of shakedown flights was made. In these flights, the airplane carried all the special systems and the noncritical reactor. With these preliminaries out of the way, the first critical flight took place.

Handling and Operation

Because the ASTR was designed as a shield-test reactor, the shielding allows a large amount of radiation to escape from the core. Consequently, the radiation levels immediately about the ASTR, even when the reactor is shut down, prohibit personnel access. To permit maintenance of the ASTR, as well as transportation between the aircraft loading pit and the reactor handling pool, it was necessary to design and fabricate dependable reactor-handling equipment.

For maintenance, the ASTR is submerged in a pool. A set of handling tools allows complete reactor disassembly by personnel located on the bridges above the pool. Figure 3 shows the ASTR in the pool (forward end up) with a fuel element being inserted into the core. In this figure the forward shields and sections of the reactor have been removed to expose the core. The ASTR is supported in a fixture that permits remote positioning underwater from aft-end up to forward-end up. Access to both ends is necessary because fuel-element loading and shield tank installation is performed from the forward end and instrumentation and control-rod drives are installed from the aft end.

When all maintenance is complete, the cradle is rotated back to its normal horizontal position and the reactor is readied for transport to the loading pit. The roof of the building housing the maintenance pool can be rolled open to permit a shielded gantry crane access to the reactor. Figure 4 shows the ASTR being lifted from the pool. The crane hook is engaged to a leveling mechanism attached to the ASTR. The shielded gantry crane can be seen in Fig. 5 lowering the ASTR onto the lift mechanism of the aircraft loading pit.

The pit contains a hydraulic lift platform. Prior to the reactor's arrival on the scene, the lift platform has been raised to its full height. The crane places the reactor on the lift, and the entire apparatus is lowered into the pit. Heavy steel doors are rolled into place over the pit when the lift is completely down.

The B-36 carries the ASTR in its aft bomb bay. A completely re-engineered nose section includes a shielded crew compartment. Air scoops on each side of the fuselage provide air to the reactor-cooling-system heat exchangers. A special shielded vehicle is used for towing the airplane into position. Shielding on this vehicle was provided so that the NTA could be towed with the reactor on board.

The airplane is towed to the loading pit and onto a turntable where the wheels of one main landing gear are chocked. With one gear on the turntable chocked, the plane is towed around in a tight circle and positioned over the loading pit. Once the plane is in position, all personnel retire to shielded areas for the duration of the loading operations. The entire procedure takes about 20 min from the time the pit doors open until the

Here's How Remote Handling of ASTR is Accomplished—

FIG. 3. Stripped ASTR in maintenance fixture in pool (ordinarily water-filled)

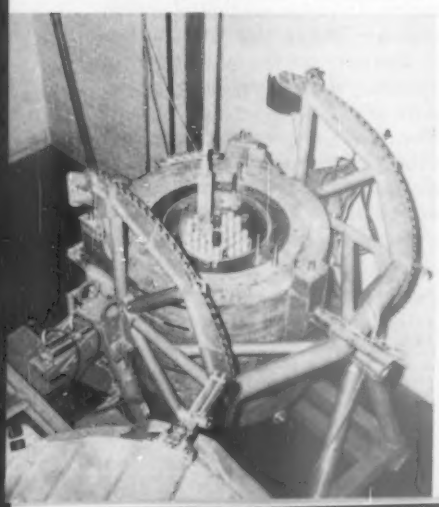
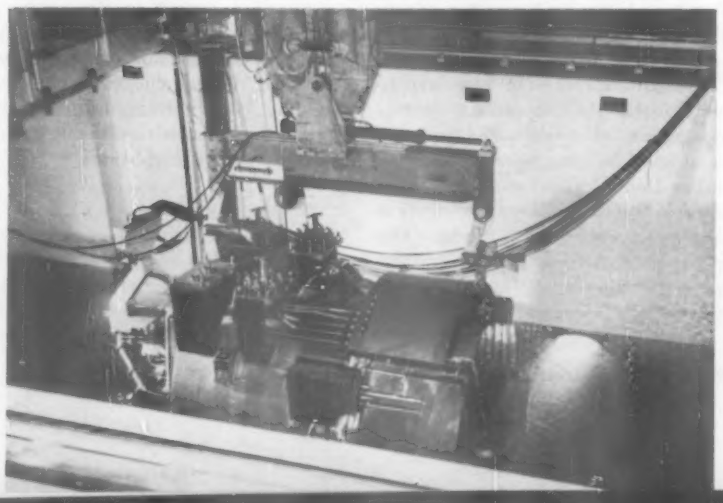


FIG. 4. Assembled ASTR being raised out of maintenance pool by crane. Electric and hydraulic quick-disconnected couplings can be seen on top of reactor



reactor is loaded aboard the plane.

The loading-pit doors are opened by the loading operator from the underground control room. During the time elapsed since the crane placed the reactor on the lift, a pre-flight check of the reactor was made, that is, it was checked to ensure that all rod drive motors were functioning, that all instrumentation was registering properly, and that all control rods could be withdrawn. The core and all shield tanks have been filled with water, and the reactor is ready to be loaded. Figure 6 is an aft view of the ASTR being loaded into the bomb bay of the NTA by the lift mechanism.

When the actual loading of the reactor into the airplane begins, the lift must align the reactor accurately to ensure that all latches and quick-disconnect panels of the reactor and airplane mate. After the panels have been mated, the reactor operator in the crew compartment is then able to operate the reactor remotely; to empty, fill, or pass moderator water through the core; or to fill any or all of the water shields in the reactor.

The lift is made up of four movable platforms for adjustments in the attitude of the reactor while it is being positioned in the airplane. The reactor may be tilted, rotated about a vertical centerline, or moved horizontally either transversely or longitudinally. When the lift attains a certain height, probes on both ends of the lift platform are extended upward until they engage their mating places in the reactor bay. At this point, indicators on the console show the lift operator the degree of misalignment of the lift, if any, by sensing the probe attitude. The lift platform is then adjusted to make the probes vertical, thereby indicating exact alignment with the airplane. After alignment has been attained, the lift drives the reactor into the bay and latches it firmly in place. When the reactor is secured and the lift has been lowered once more into the loading pit, the bomb-bay doors are closed and the airplane is ready to begin its flight.

The NTA, now loaded with the reactor, taxies out of the exclusion area to the runway. Here the pilot checks out the various functions of the airplane under his surveillance. Meanwhile, the coolant-moderator water is being completely drained from the reactor core as an added safety precaution during take-off.

During the take-off and subsequent flight, an escort plane (modified B-50) follows the NTA. Personnel in the escort plane watch for any difficulties which the NTA crew might not detect. The airplanes fly cross-country through a preselected flight corridor to an isolated area where the actual reactor operations are carried out. A flight may not take place unless perfect or near-perfect weather conditions exist over the entire operations area.

After arrival at the test area, the core of the reactor is filled with water. The reactor operator starts the reactor by withdrawing the control rods in the standard operating sequence. The safety rod is withdrawn first, the regulating rod next, and finally the shim-safety rod. When the desired conditions of operation are reached, the reactor power is stabilized and the recording of data begins. Radiation levels are measured by the nuclear engineer in the shielded crew compartment as well as in the remote portions of the airplane. Detection and measurement of air-scattered radiation are made by the specially-instrumented escort plane.

Upon completion of the data runs, the reactor is shut down and the planes then return to their home base by way of the same flight corridor through which they flew on the way out. During the return trip, cooling water is circulated through the reactor core to remove the residual heat; however, before the plane lands, the moderator water is drained from the core.

During the extensive experimental flight program carried out since that first flight (spanning a period of over 20 months), the ASTR has been operated frequently up to maximum power on a routine basis. The reactor and its associated systems have proved to be exceptionally reliable and operations on the ground and in the air have been gratifyingly trouble-free. Engineering experience gained through this program has proved that the design and systematic operation of highly mobile reactor systems, while by no means effortless, is well within the scope of present reactor technology.

From Maintenance Pool to Loading Pit and into B-36 Bomb Bay

FIG. 5. Shielded gantry crane transports ASTR to aircraft loading pit where hydraulic lift is fully extended. Airplane is rolled over pit by shielded tractor

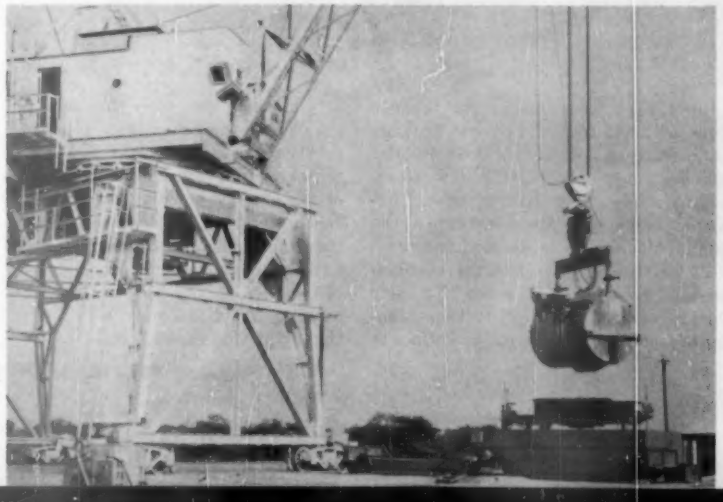
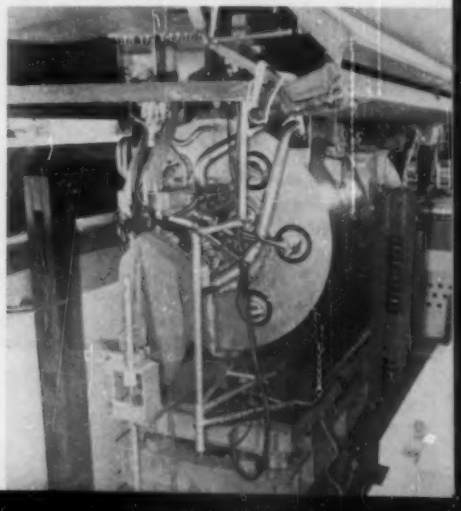


FIG. 6. ASTR being raised into airplane bomb bay by hydraulic lift



Plutonium Recycle Test Reactor

By R. M. FRYAR
Hanford Atomic Products Operation, Richland, Washington

THE PLUTONIUM RECYCLE TEST REACTOR is part of a program to develop the technology of thermal heterogeneous power reactors using a plutonium fuel cycle.

The reactor design described here was not selected as an optimum type for the uranium-plutonium cycle, but as a facility for experiment and testing. The reactor is to provide data on nuclear physics, fuel-element design and performance, and engineering technology that are essential to the plutonium-recycle concept, including, but not necessarily restricted to, the self-sustaining cycle.

Physics tests will yield information on critical startup conditions, reactor-control characteristics and the reactivity effects of various lattice parameters and operating conditions. Such information as long-exposure characteristics, isotope composition and material balance under both equilibrium and nonequilibrium conditions is necessary to reduce the cycle concept to a practical design.

A number of fuel-element designs will be tested. Finally, the test reactor must provide irradiated fuel for reprocessing and refabricating studies.

For the initial loading, about 35% of the fuel elements will be spike-enriched with plutonium and the remainder will be natural UO_2. It is expected that the UO_2 will be of PWR grade, extruded or pressed and sintered to about 90% theoretical density. Subsequent loadings may be uniformly enriched. Burnup target for the UO_2 elements will be about 5,000 Mwd/ton.

A leading candidate for the uranium loading is a concentric-cylinder assembly jacketed in Zircaloy-2 or perhaps Zircaloy-3. It is anticipated that the plutonium-enriched elements will have plutonium-aluminum alloy cores. These elements may be in the same form as the feed-fuel elements or in the form of a 19-rod cluster.

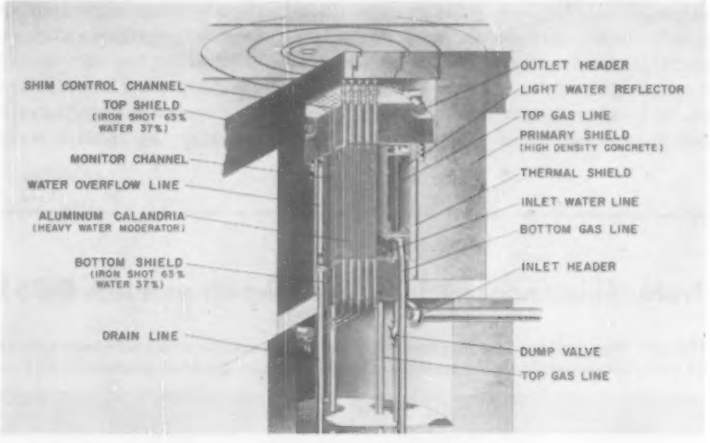
Construction of the reactor is to start in early 1958. Startup is scheduled for the spring of 1960.

* * *

This article is based on papers presented at the Atomic Industrial Forum, New York, October, 1957, and at the AEC-ASM-sponsored Conference on the Metal Plutonium, Chicago, November, 1957.

1. REACTOR CORE . . .

is contained in an 84-in.-i.d., 115-in.-high aluminum tank. In this calandria are 85 fuel, 18 shim-rod-control and 13 flux-monitoring channels. The 85 fuel tubes are arranged on an 8-in. equilateral triangular lattice. A double-tube arrangement insulates the low-temperature moderator from the high-temperature primary coolant—the outer (shroud) tube, part of the calandria, is made of aluminum; a ¼-in. helium thermal insulating gap between shroud and process tube restricts heat flow to the calandria to <1 Mw. The Zircaloy-2 fuel tubes will be 3.250 ± 0.010 in. i.d. with a 0.154 ± 0.008-in.-thick wall in the reactor core; the lower end of the tubes will be tapered to a 2-in. o.d. with a greater wall thickness for ease of assembly at the lower face piping.

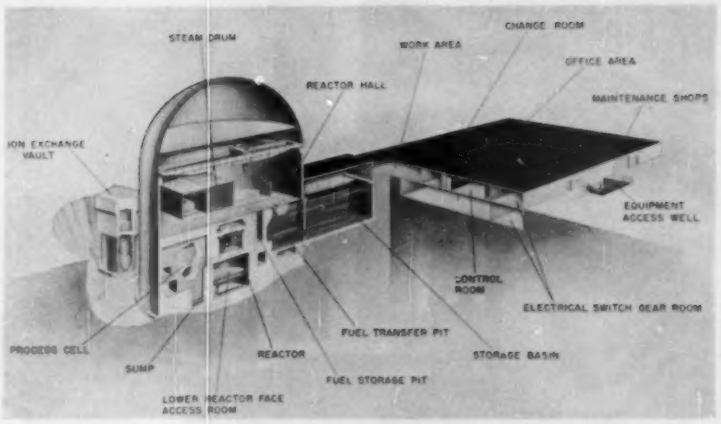


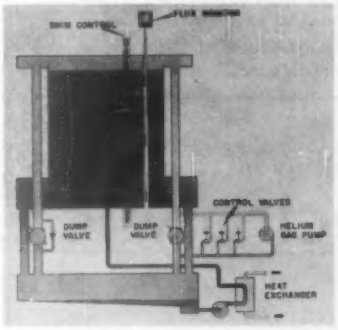
An annular dump chamber, attached to the lower end of the calandria, is a collecting header for moderator effluent that spills over a weir and also serves as a temporary storage volume for moderator during a reactor scram. About 65% of the moderator effluent flows through the drain header to the moderator tank, the remainder flowing over the dump-chamber weir. Moderator flow is about 1,100 gpm with a temperature change from 137° F to 160° F. Heavy- or light-water reflector is contained in an annular cylinder (11-ft o.d., 7-ft i.d., 6 ft 10 in. high) outside the calandria tank. Reflector circulation is about 300 gpm at the same temperatures as the moderator.

Biological shielding surrounds the calandria and reflector on all sides. The side shield is 71-in.-thick, 21-ft-deep high-density concrete. The inside surface is a ½-in.-thick steel liner that serves as a gas seal for the helium atmosphere. Inside the liner is a thermal shield of 12-in.-thick cast iron, which absorbs about 90% of the energy escaping from the core. Bottom and top shields are 40-in.-thick steel tanks filled with iron pellets (63% by volume) and water, giving a density of 285 lb/ft³. Above the top shield is a rotating shield assembly with an eccentrically located access hole.

2. TEST REACTOR . . .

is housed in an 80-ft-diameter containment shell extending 75 ft above grade. Shell design pressure is 15 psig; although it is planned to use heavy-water coolant, which in the worst possible incident (coolant-header failure) would create a pressure of 3 psi, the shell is designed to contain a light-water incident, which could involve a pressure of 12.5 psi. About 66 Mw of heat is removed by heating heavy water from 480° to 530° F; the 8,400-gpm coolant flow to the steam-generator heat exchanger is cooled by boiling ~206,000 lb of water into 425-psia saturated steam. Most of the steam is condensed in the Columbia River in a jet condenser.





3. PRIMARY CONTROL . . .

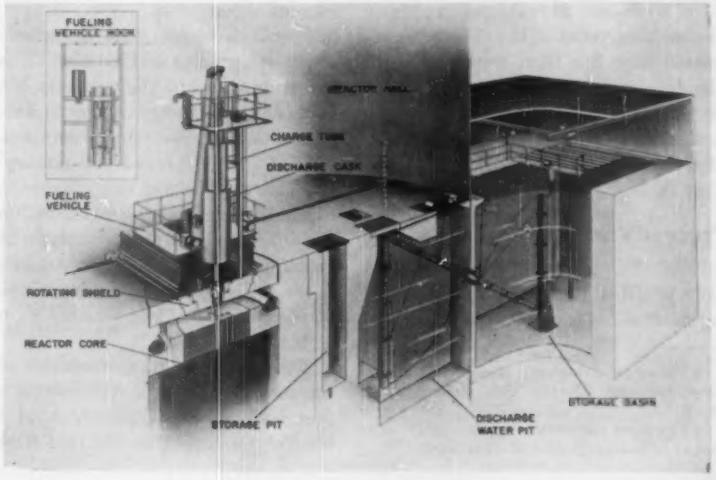
is based on variation of reactivity by variation in the moderator level in the calandria. Moderator level is controlled by applying a differential helium gas pressure across the moderator surface in the calandria and the surface at the annular weir in the dump chamber. When the pressure differential is established, flow over the weir will be suppressed and the moderator will seek a level at which the liquid head exactly balances the applied pressure differential. The maximum rate of reactivity increase is governed by increases in moderator level, which is limited by the capacity of the helium system. The helium system is made small enough to limit the reactivity increase rate to a value less than the response time of the control system. Moderator level will be automatically controlled by signals from either neutron-flux level or reactor period or both.

A shim control system is provided for close adjustment of reactivity. Primary purposes are: (1) maintenance of normal moderator operating level, (2) compensation for fuel burnout, (3) provisions for xenon override and flattening of the neutron flux, (4) depression of flux. Shim-control operation is manual and not intended as a safety device. Each shim unit consists of two half-rods about 3 ft long. Each rod is individually positioned by a miniature stainless-steel stud chain driven by a geared miniature electric motor. Rod positions are transmitted to the control room by synchro transmitter linkages. The rods are self-contained units, easily replaceable.

Reactor scram is accomplished, automatically or manually, by equalizing the gas pressure between the top gas plenum and the moderator storage tank. Moderator flows out of the calandria at an average rate of 20,000 gpm; within 0.7 sec, moderator level falls 2 ft.

4. THE CHARGE-DISCHARGE MACHINE . . .

is about 25 ft high and weighs 50 tons. The vehicle is controlled by an operator riding it. New, nonirradiated fuel elements are stored in the pit under the reactor-hall floor. For discharging, a fuel element is withdrawn by the vehicle into the discharge cask and carried to an underwater transfer carrier. The carrier is tipped into an inclined position and the element rolls out of the reactor containment vessel onto conveyor tracks in the storage basin, where the assembly is again set upright. The basin is equipped with a bridge crane for moving elements to the desired storage position.



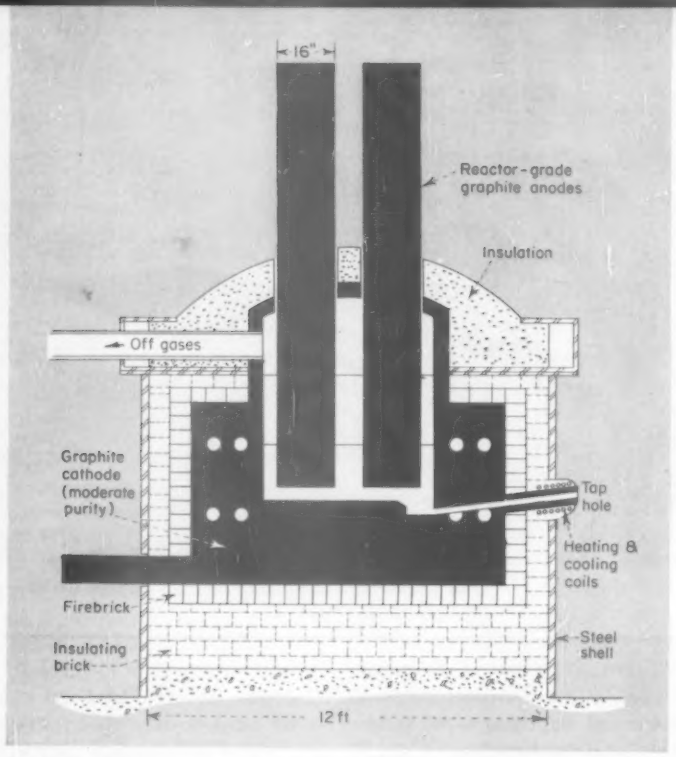


FIG. 1. Conceptual design of cell for continuous reduction of uranium

TABLE 1—Cell Operating Conditions

Yield of metal (kg/day)	1,000
Current, amp (at 75% eff.)	25,000
Bath composition (mole %)	
UF_4, 20; MgF_2, 40; BaF_2, 40	
Feed rates (kg/day)	
UO_2	1,200
Graphite anodes	100
BaF_2 makeup	0.1
MgF_2 makeup	0.3
UF_4 makeup	2.5
Anode area (in^2)	1,210
Anode diameter (in.)	16
Depth of anode immersed (in.)	2
Number of anodes	4
Cathode area (cell cross section plus immersed walls, in^2)	3,380
Depth of wall immersed (in.)	5
Anode current (amp/in^2)	21
Cathode current (amp/in^2)	7.4
Cell cross section for gas flow (in^2)	1,600
Gas produced at 1,200° C (ft^3/min)	25

New Approach to Electrolytic U

By L. W. NIEDRACH,* B. E. DEARING and A. C. SCHAFER†
Knolls Atomic Power Laboratory
Schenectady, New York

METALLIC URANIUM is currently prepared by the bomb reduction of UF_4 with Mg metal (*1*), a batch process requiring several steps. However, electroreduction of UO_2 directly to the metal is amenable to continuous operation when run at temperatures above the melting point of U. The work reported here has been concerned with the development of a process analogous to the Hall process used for aluminum production. It has resulted in the design of a production-scale cell (see Fig. 1).

Process Variables

While UO_2 is the preferred oxide feed for a practical process, UO_2 was chosen for most of the laboratory work in testing the effects of variables. This choice was made because the CO produced in the electrolysis reduces UO_2 chemically to UO_2 without requiring an applied electromotive force. Only the reduction of UO_2 to metal consumes current.

Operating temperature is limited by the melting point of U, 1,130° C, as a lower limit, and by the volatility of the salts and reactivity of the metal at high temperatures. A temperature of 1,175–1,200° C proved satisfactory in the laboratory work.

It is important that decomposition of the diluent salts in the electrolytic bath be minimized. The most satisfactory baths tested were equimolar mixtures of MgF_2 and BaF_2 to which UF_4 was added.

The most important variables were the magnitude of the electrolysis current and the U-salt content of the electrolytic bath (see Fig. 2). Lower efficiencies with high UF_4 content appear to be related to the fact that at high concentrations a fair portion of the electrolysis current can be carried by cyclic oxidation and reduction between two valence states, presumably U^{+3} and U^{+4}. However, at relatively low concentrations it is impossible to operate with high currents because of polarization at the anode. It was concluded from these data that the 20 mole % UF_4 bath is about the optimum.

According to Fig. 2, an optimum efficiency is apparently obtained by operation at 50 amp. The peak at this current is actually related to the fact that, in all of the tests, the 50-amp operating point was the first one of a series at different currents. Any oxide originally present in the salt bath as impurity was therefore available for electroreduction at this time and added to the apparent efficiency of operation during that increment. Thus it would

* PRESENT ADDRESS: Research Laboratory, General Electric Co., Schenectady, N. Y.
† PRESENT ADDRESS: Oak Ridge National Laboratory, Oak Ridge, Tenn.

appear that operations at 50, 70 and 90 amp are essentially equivalent. The lower efficiency at 25 amp, however, seems to be quite real.

Under the test conditions, operation at 50–90 amp corresponded to anode current densities of 5.2–9.7 amp/in^2. With the 20 mole % UF_4 bath, operation was actually pushed to anode-current densities as high as 23 amp/in^2.

It would appear from Figs. 3 and 4 that the UO_2 was inherently more easily reduced, but that because of a larger average particle size the net reduction efficiency was less with this material than the others.

In all cases the efficiency of reduction was <100%. This is largely because the solubility of UO_2 in the salt electrolytes is low and the oxides that were tested all settled rapidly in the baths. In addition, the settled oxides also generally prevented the product metal from agglomerating into compact billets. This settling problem is considered the most important remaining development problem. However, through the proper choice of oxide and particle size the problem may be eliminated.

TABLE 2—Estimated Plant Cost*

	Yearly cost	*Cost per lb of U*
Total plant investment		
$7,847,000 amortized at 20%/yr	$1,569,000	$0.195
Direct operating costs		
Labor	$ 355,000	
Supplies	1,468,000	
Utilities	228,000	
	2,051,000	0.255
Indirect operating costs		
Labor	267,000	
Supplies	79,000	
Utilities	70,000	
Payroll overhead, local taxes, insurance	197,000	
	613,000	0.077
Total cost	$4,233,000	$0.527

If a 25% return on investment (before taxes) is desired, an additional $0.129 would be added to the above costs.

* Basis: 10 long tons/day capacity and 365 days/yr operation.

CO and CO_2 were the major gaseous anode products. The CO content was 75–82%, and no correlation with the magnitude of the electrolysis current was evident. In the run with the 10 mole % UF_4 bath, the CO content fell to 50%. In this case 4–10% CF_4 was also found. The CF_4 content with the 15 mole % UF_4 bath averaged slightly less than 1%. In all other cases the CF_4 content of the off-gases was equal to or less than 0.1%. Neither O_2 nor F_2 was ever detected in the off-gases.

Product analysis gave low analyses for oxygen (4–6 ppm), barium (<200 ppm), magnesium (7–20 ppm) and hydrogen (<1 ppm), all constituents of the baths. Major impurities were Al and Si (both >1,000 ppm), which were undoubtedly obtained from structural materials and could be avoided. Carbon contents of about 600 ppm were felt to be reasonable in view of the use of graphite cells.

Electrolysis Cell

An electrolytic cell having the operating conditions listed in Table 1 appears reasonable. The cell dimensions are largely determined by electrode current densities. It is necessary to keep the immersion depth of the anodes low to facilitate attack from the bottom. This causes a relatively large cell cross section.

Four 16-in.-diam electrodes would be fed continuously through the cell cover. Electrical input would be 25,000 amp at approximately 5 volts, d-c.

Graphite was chosen for the cell lining in spite of the fact that U has a finite solubility for C and also forms carbides. Preliminary data (*2*) support the assumption that the carbide layer at the interface will be protective. Nevertheless it is assumed that the metal itself will saturate with C at about 500 ppm. The cell bottom would corrode at a rate of 2.6 in./yr, which is assumed to be the life of the lining.

The oxide feed would enter through a port (not shown) in the cover of the cell. The tapping operation will probably be done in air, a procedure not without precedent for U (*3*).

Cost Estimate

A preliminary cost estimate is given in Table 2. Two aspects of the cells present cost-reduction opportunities. First, the cells contribute about $3,000,000 to the plant investment. Second, replacement of the cell liners contributes about $1.3 million per year to the operating cost. Higher-capacity cells, such as used in the aluminum industry, will lead to a reduction in the plant investment. Reduction in the operating costs can be achieved if the useful life of the cell linings exceeds the assumed 1 yr.

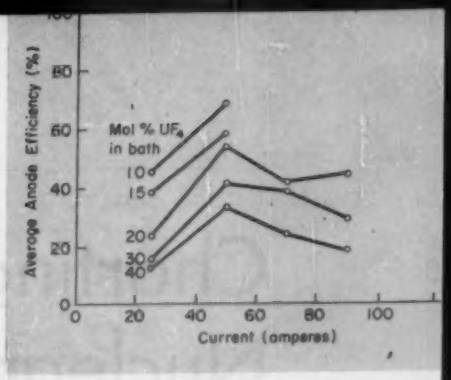


FIG. 2. Effect of current and salt-bath composition on reduction efficiency

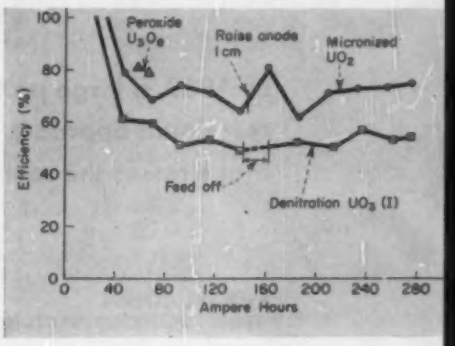


FIG. 3. Behavior of several oxides

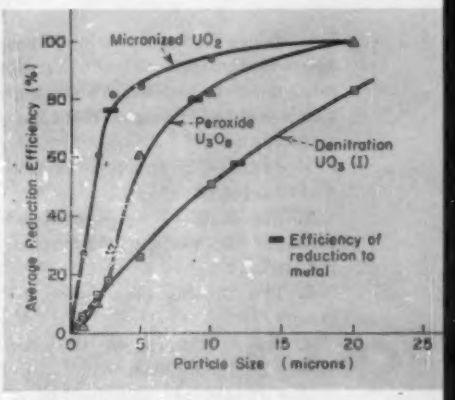


FIG. 4. Effect of particle size on reduction efficiency

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Charting a Course for Nuclear Power Development

By 1980, a large part of our electric power will be nuclear in origin. A rational approach to long-term reactor economics is proposed that stresses the role of realistic material and capital costs

By KARL COHEN
Atomic Power Equipment Department, General Electric Co., San Jose, California

THE CHOICE OF A REACTOR TYPE appropriate for the development of a national nuclear power system involves a great many factors. Some of the most important are:

1. Availability and price of nuclear and conventional fuels.
2. The state of technical development of the nuclear and competing industries.
3. The requirements for electrical energy.
4. The economics of the nuclear energy complex as a whole.

The weight of these factors varies from country to country and with time. Thus, there is no single best reactor type.

However, since the development of an excessive number of reactor systems is expensive, we must make a selection. Further, the scale of nuclear operations is rapidly increasing, and changing course in the future will be enormously expensive.

In the evaluation presented here, three reactor types are discussed to illustrate the approach. It is recognized that intermediate designs as well as other types may prove feasible. The discussion is further framed in terms of the projected U. S. domestic economy. However, the results may be easily applied to other situations.

Reactor Types

Three principal reactor systems are competing for recognition. They are the water-moderated enriched-uranium-fueled reactor, the graphite-moderated natural-uranium-fueled reactor and the heavy-water-moderated, natural-uranium-fueled reactor. The belief is not uncommon that water reactors make extraordinary demands on raw materials (uranium) and capital (diffusion plants), which makes them unsuitable as a basis of a national power economy unless the diffusion plant can be written off for other purposes. This makes comparison of the three reactor types on purely economic grounds seem superfluous. In this article we shall accordingly investigate first the uranium requirements of water and graphite reactors,* and then the capital requirements of diffusion plants and heavy-water plants as they would apply to a rapidly growing nuclear-power economy. The discussion will be based on the assumption that the economy will use all water plants, all graphite plants or all heavy-water plants.

We shall find that the uranium requirements for natural-uranium-graphite and enriched-uranium plants are comparable and, when recycling is factored in, not large enough in either case to warrant concern over short supply before 1980. The capital requirements for diffusion plant, per kw of power plant supported, are quite moderate, so that reactors using enriched fuels have a perfectly sustainable *economic* justification.

Since the foregoing results show there is no unbridgeable discontinuity between the various reactor types, our prime concern must be with the measures used for determining comparative economic usefulness. The balance of the article highlights the problem of capital accumulation for nuclear power plants. We conclude that appropriately high capital charges on plant, fuel inventory and other special materials in cost studies *now* are the best guarantee against exorbitant capital expenditures in the future.

Finally, we do not intend to imply that the considerations presented suffice (in the absence of capital-cost information) to choose between the three reactor systems discussed.

* It is premature to assess the uranium requirements of heavy-water reactors. There is considerable difference between preliminary designs from Chalk River and Savannah River, both organizations having considerable experience in heavy-water reactors. The more optimistic designs indicate very low requirements.

This Power Growth . . . Requires This Much Enriched U . . . Or This Much D_2O

Year	Total installed Mw(e)	Nuclear installed Mw(th)	Enriched-uranium requirements (tons)*					Heavy-water requirements (tons)†	
			Inventory	Cumulative throughput	Cumulative requirement	Annual requirement	Equilibrium throughput	Cumulative requirement	Annual requirement
1960	180,000	2,000	200	0	200	200	50	480	480
1965	250,000	9,000	900	95	1,000	400	225	2,160	756
1966		12,100	1,210	185	1,400	550	300	2,920	1,110
1968		22,100	2,210	475	2,690	990	550	5,310	1,850
1970	360,000	40,000	4,000	1,010	5,010	1,850	1,000	9,600	3,470
1972		73,400	7,340	1,970	9,310	3,250	1,840	17,600	6,040
1974	474,000	133,200	13,320	3,730	17,050	6,050	3,330	32,000	11,200
1975	509,000	180,000	18,000	5,100	23,100	7,800	4,500	43,200	14,400
1976	546,000	240,000	24,000	6,900	30,900	11,320	6,000	57,600	21,200
1978	627,000	444,000	44,400	12,800	57,200	19,500	11,100	107,000	35,600
1980	720,000	754,000	75,400	23,500	98,900		18,800	180,000	

* Assume all domestic power plants use uranium enriched to 1.5%. Equilibrium throughput is the amount of enriched uranium required per year on a long-time basis to support the plants already built but not to increase their number.

† Assumes all domestic power plants use heavy water.

Nuclear Power Growth

Projections of the installed generating capability in the U. S. (*1*) indicate about 180-million kw in 1960, roughly doubling every 10 years thereafter (see Table 1, above). The same increase (~7%/yr) is expected in Europe (*2*).

A conservative (high) estimate of nuclear fuel requirements is obtained by an optimistic projection of the nuclear generating capability. The nuclear generating capability in the U. S. will be 2,000 Mw(th) in 1960. We assume it to increase at the rate of 35%/yr until the rate of growth overtakes that of total power. This leads to 754,000 Mw(th) in 1980.*

Except for 1979 and 1980, the growth rate is approximated by

$$P \text{ (installed capability)} = 2{,}000e^{0.2t} \text{ Mw(th)}$$

For such a steep gradient, the principal requirement of nuclear fuel will be for inventory. We shall therefore look into this term somewhat carefully.

Enriched-Uranium Requirements

If the average specific power in the reactor is K Mw(th)/ton, the fuel lifetime is T Mwd/ton, and f is the plant load factor, then the average in-pile residence time is T/Kf days. Now if this is sufficiently large, all other contributions to inventory will be minor.

For a typical first-generation reactor (the Dresden Nuclear Power Station), the in-pile residence time is about 1,300 days; the fabrication time is 300 days; cooling and reprocessing is another 180 days. Including 20% spares, the out-of-pile inventory is 57% of the in-pile inventory. The total inventory [K = 11 Mw(th)/ton] is about 1 ton of 1.5%-enriched uranium per 7 Mw(th).

Under present arrangements, where fuel inventory is financed at 4%, the inventory cost of fissionable material is about 0.37 mill/kwh.† With conventional financing, the inventory cost would be nearer 1.3 mill/kwh, which would be painful. Either to conserve the supply of fuel available at 4% financing or to prepare for higher inventory charges, reactors will be designed with higher specific powers, and outside inventory will be correspondingly tightened up. There are no foreseeable difficulties in reaching 1 ton/10 Mw(th). In 10 years or so, to reduce plant capital costs, we anticipate 1 ton/15–20 Mw(th) will be the design target. In calculating the requirement of enriched fuel, we shall use the lower specific power, 1 ton/10 Mw(th).

During the 20-year period 1960–1980, when the number of nuclear plants is increasing rapidly, burnup will be a lesser burden on fuel supplies. However it cannot be neglected. Assuming the fuel goes through the reactor only once, the throughput is 365 f/T tons/yr/Mw(th), which for Dresden (f = 0.7, T = 10,000 Mwd/ton) is 2.5×10^{-2} ton/yr/Mw(th).

The total inventory of fissionable material required is $0.1P(t)$; and the cumulative throughput is

$$2.5 \times 10^{-2} \int_{3.5}^{t} P(t - 3.5)\, dt$$

accounting for the 3.5-yr delay between input and output of 10,000 Mwd/ton fuel. These functions are tabulated in Table 1.

So far we have considered all power production to be from thermal reactors. If breeders are successful, they will be started on plutonium. Thus any proportion of breeders will decrease U^{235} requirements correspondingly.

Natural-U Requirements

The most recent design of a gas-

* In agreement with the consensus of predictions given in NUCLEONICS, September, 1957, p. 91.

† In this calculation account is taken of the progressive depreciation in value of the fuel during irradiation.

cooled, natural-uranium, graphite-moderated reactor is that of Hinkley Point. The output per reactor is 980 Mw(th) and the fuel inventory is 300–400 tons. Counting outside inventory, a value of 1 ton/3 Mw(th) seems appropriate to compare with the 1 ton/10 Mw(th) of a water reactor of the same generation. The inventory of natural uranium is therefore taken as $\frac{1}{3}P(t)$. The fuel lifetime is taken as 3,000 Mwd/ton. The throughput, again with 70% load factor, becomes 8.5×10^{-2} ton/yr/Mw(th), and the cumulative throughput is

$$8.5 \times 10^{-2} \int_{3.5}^{t} P(t - 3.5)\, dt$$

again allowing for a 3.5-yr residence time in the reactor.

The natural-uranium requirements for graphite reactors of the Hinkley Point type are found by multiplying the enriched-uranium figures in Table 1 by $1\frac{1}{3}$. For comparison purposes we must remember that it takes over 2.5 tons of natural uranium to make 1 ton of uranium with 1.5% U^{235} content. The annual natural-uranium requirements for either system (assuming no fuel recycling) are thus approximately equal and reach about 60,000 tons/yr in 1980.

Here it is worth noting that plutonium recycle will have an important effect. By using Pu to enrich a gas-cooled graphite reactor, substantially higher specific powers and better burnup may be expected. Surely these two factors would reduce the annual uranium requirement by a factor of 2.

In the enriched-uranium system, the material discharged from the reactor has a concentration of about 0.7%. Without any assistance from the plutonium, we thus have an eventual factor of 1.5/2.5 on the uranium requirement. Plutonium will permit some reduction in the enrichment required. If the reduction is only to 1.2% U^{235}, the natural-uranium feed to the diffusion plant would drop from 2.56 tons/ton of reactor fuel to 1.96.

Thus the actual requirement of natural uranium for the U. S. domestic economy would not exceed 30,000 tons/yr over the entire period projected, for either reactor system. It is estimated later in this article that present feed rates to the diffusion plants are about 15,000 tons/yr. Doubling this amount over the next 23 yr will be no problem.

TABLE 2—Cost of U. S. Enriched-Uranium Production

Item	*Annual charge (millions)*
$2.3-billion at 10% (7) depreciation	$230
Power, 50-billion kwh at 4.1 mills	205
Operating personnel, 10,000 at $7,000*	70
Maintenance at 2%*	46
	$551
AEC overhead at 15% (7)	83
	$634

* Estimated.

Heavy-Water Requirements

Limiting the inventory of heavy water is already a well established design criterion for heavy-water reactors. Values of 0.8 ton D_2O/Mw(e) [or 0.24 ton/Mw(th)] are attainable (3). We adopt this figure for calculation purposes. Assuming that no heavy-water makeup is required and that all domestic power plants use heavy water, the cumulative requirement in tons of D_2O is $0.24P(t)$.

Table 1 shows the cumulative and annual requirements of heavy water based on these assumptions.

Enriched-Uranium Availability

The amount of enriched uranium available from the U. S. diffusion plants can be estimated from published unclassified data.

Let us assume that the price established by the AEC for enriched uranium is consistent with the manner of financing that has been used for other AEC processing operations. We know the capital investment represented by the total diffusion-plant operation is approximately $2.3-billion (4). We know the amount of electricity consumed by the AEC,* its average price (4) and the total number of people employed in the three diffusion plants (5). Based on normal engineering salary levels, operation and maintenance costs can be roughly estimated.

Further, of the $17/gm price of enriched uranium, approximately $8 must represent the cost of the feed that is used (6). Therefore, the total of the capital and operating costs of the diffusion plants, divided by the price per gram of uranium after subtracting the feed cost, is a rough estimate of the total annual production rate.

There are, of course, many details of the exact mode of operation and optimization of a diffusion cascade that we cannot take into account. For example, the uranium effluent of the Hanford and Savannah River plutonium plants amounts to a large tonnage of slightly depleted feed, and if this is used as feed, it would decrease somewhat the amount of enriched product available. Omissions from the cost totals, conversely, would raise the amount available. Nevertheless, for the accuracy required for the present discussion, this estimate of the annual production rate cannot be far in error. It is reasonable to assume that the 13 years of operating experience and improvements in successive plants probably compensate for the factors that we have omitted here.

The cost of 90%-enriched uranium is $17,070 per kg of contained U^{235} (8). The portion of this cost represented by feed material is $8,000. From Table 2, one can make the estimate

$$\frac{\$634 \times 10^6}{\$9{,}070/\text{kg}} = 70{,}000 \text{ kg/yr } U^{235} \text{ in } 90\% \text{ enrichment} = \sim 85 \text{ short tons of } 90\%\text{-enriched uranium/yr}$$

If the cascade is operated to produce 1.5% material, the separative work per unit of product is about 200 times less; so, assuming sufficient feed,† the production capability becomes

$$200 \times 85 = 17{,}000 \text{ tons/yr of uranium enriched to } 1.5\%$$

According to the foregoing estimate, the production from $\frac{1}{3}$ of the existing diffusion plants would sustain indefinitely a nuclear power industry of 70,000 Mw(e), which we would not expect to achieve before 1976. If one of the diffusion plants were assigned to the task in 1970, it would also be able to build up the necessary fuel inventory. The investment in diffusion

* Total AEC power use in 1956 was 58.5 billion kwh (1). Assume $\frac{1}{6}$ is used outside of diffusion plants.

† The feed to produce 70,000 kg of U^{235} per year would be 15,400 short tons of natural uranium per year. To produce a mix of $\frac{2}{3}$ U^{235} at high enrichment and $\frac{1}{3}$ 1.5% U^{235} would require a feed of $\frac{2}{3} \times 15{,}400 + (17{,}000/3) \times 2.56 = 24{,}800$ tons. (See ref. 7 for basis of calculation.)

plant per kilowatt of nuclear power, at the point where plant output equals inventory plus burnup requirements, is about $17/kw;* at the point where output equals burnup, it is $11/kw. The power input to diffusion plants supporting 70,000,000 kw(e) is 2,000,000 kw(e). These figures are based on characteristics of a boiling-water reactor, not significantly different from a plant in construction, and they make no allowance for extending the fuel by recycling the plutonium.

Heavy-Water Availability

An estimate of the amount of heavy water available from U. S. heavy-water plants can likewise be made from published unclassified data. From Table 3, one can make the estimate

$$\frac{\$60 \times 10^6/\text{yr}}{\$28/\text{lb}} = 2.1 \times 10^6 \text{ lb/yr}$$

$$= 1{,}100 \text{ tons/yr}$$

To sustain the domestic power industry to 1970, the production of both existing heavy-water plants would have to be assigned to this purpose in 1961. By 1966, production at the current level would be below demand. The investment in heavy-water plants at the cross-over point turns out to be $59/kw(e).

During the next 20 years the D_2O plant could furnish inventory for 20×1.3 million kw(e), at which time the investment would have fallen to $9/kw. However, $59/kw(e) is the proper figure for D_2O-plant investment to keep up with a nuclear power industry growing at the projected 35%/yr rate.† If heavy-water reactors are a fixed percentage of a rapidly growing nuclear economy, the investment per kw is not lowered. But in a more slowly growing economy—~10%/yr—it is reduced to more manageable terms.

Therefore: We arrive at the unexpected conclusions:

1. For an expanding nuclear economy, it is far cheaper to invest in diffusion plants than in heavy-water plants (on today's technologies).

TABLE 3—Cost of U. S. Heavy-Water Production

Item	*Annual charge (millions)*
$264-million (*11*) at 10% depreciation	$26
Operation and maintenance (guestimate)	26
	$52
AEC overhead at 15%	8
	$60

2. A fraction of existing diffusion plants can support an order-of-magnitude-larger power economy than both existing U. S. heavy-water plants.

3. In a slow-growing nuclear economy investments in heavy water and diffusion plants are comparable.

Capital Charges

The preceding analysis shows that neither uranium supply nor capital investment in plants for producing enriched uranium or heavy water is by itself a determining factor in the choice of a reactor system.

We are therefore led to straight economic comparisons. Here, the most important consideration is the capital charge.

Capital charges on any type of plant cover three factors: (a) return on the capital, (b) amortization, and (c) taxes. The purpose of the first is to supply new capital for the expansion of the industry. If new plants have higher capital costs than their predecessors, the balance is upset—the accumulation of new capital must be increased.

Our assumed growth curve for the nuclear industry indicates a 35% per year increase within a power industry whose over-all annual increase is 7%. On this simplified model, when ⅕ of the industry is nuclear, the entire increase would be nuclear. If nuclear plants at that time cost 1.5 times more than conventional plants, the capital requirement would be 1.5 times as large, but the base would still be largely conventional plants. This would pose financial problems. Partly for this reason, the assumed growth rate will not occur until the nuclear-plant costs closely approach conventional ones.

The capital problem can be hidden, but not escaped, by distributing the burden over the whole national economy instead of merely the power sector. Whether it is done by private or public capital, transforming to high-cost nuclear plants on a crash program will create serious capital shortages. Reactor evaluation should recognize this factor by using an appropriately high capital charge. In this country it has been usual to use 12–15%, which is normal utility financing practice. From the previous discussion it is clear that this figure is valid when either:

1. Nuclear plants are an insignificant fraction of all power plants, or

2. Nuclear plant costs are not significantly larger than conventional plant costs.

In foreign countries where the need for increased electric power is more acute and the national economy base is smaller, the real cost of invested capital is not less. The important strategic consideration that $100/kw extra invested in a nuclear power plant would save $20/yr of imported coal should not lead us to forget that the same $100 in a motor bike factory would be expected to return more than $20/yr. Thus, while Europe needs atomic power plants for strategic reasons, the choice of reactor type should be made using realistic economic weighting factors. Since the European total power-growth projection is similar to ours, it is clear that their weighting factor should not be different. The conclusion is that the same type of reactor is appropriate for both the U. S. and Europe.

Fuel Costs, Load Factors

The choice of a fuel is an important consideration in reactor design. Fuel costs are presently only a small proportion of total nuclear power costs—20 to 30%—and, in particular, are small compared with the capital costs. However, the prospect of radical improvement in the capital costs, and an eventual end to government sources of fuel, materials and services, makes the fuel cycle somewhat more significant in long-range planning.

The previous discussion shows that supplies of enriched uranium available from government sources are substantial. Nevertheless they might be expected to become tight in about 20 years, which is within the lifetime of first-generation reactors. While long-term fuel agreements on a first-come, first-served basis could freeze a 4% fuel-use charge for some power stations,

* Contrast with earlier estimate by Davis (*9*) of $40–80/kw. His estimate includes the electric power stations feeding the diffusion plants (according to this estimate, $6/kw). Lane has already suggested (*10*) that Davis' results may be conservative by a factor of 3. The difference is presumably in the estimated inventory requirements.

† Compare with Davis' $30–50/kw. Each 1% of D_2O inventory required for annual losses increases the $1 kw(e) figure by $2.

this procedure would sharpen the fuel-inventory problem prematurely for many more. It is probable that after 1975 (if not before) additional diffusion plants for the civilian power market would be privately financed, and reactor fuel would be sold as an ordinary commodity. It cannot be expected that society will subsidize indefinitely the production of special nuclear materials. The conclusion is inescapable that a gradual increase of fuel-inventory charges should be anticipated. This will apply to natural as well as to enriched uranium.*

We cannot determine exactly how fuel and heavy water will be financed in the future. It is prudent to assume they will not be treated differently from other capital items. Consequently, advance reactor designs should be tested with a 14% fuel-inventory charge (and about 12–13% D_2O-inventory charge†). It will be seen at once that low-specific-power reactors are at a fatal disadvantage.

Another extremely significant factor in economic comparisons is the plant load factor. The costs that continue whether the plant is running or not are:

1. Capital charges.
2. In-pile fuel-inventory charges.
3. Most labor.

The costs that are proportional to load factor are:

1. Fuel burnup charges and credits.
2. Replacement fuel fabrication costs.
3. Chemical recovery costs.
4. Out-of-pile fuel inventory charges.

A high load factor reduces the importance of capital charges and fuel inventory, and increases the importance of fuel burnup and fabrication charges. The average lifetime load factor of plants in U. S. utility practice is below 60%. However there are some reasons for believing that early nuclear plants will be "base-loaded" to a certain extent.

The possibility depends on whether the variable costs‡ are substantially lower than the corresponding costs of conventional plants. If we take a fossil-fuel cost range of 20–30¢/MM Btu, and a thermal efficiency of 9,000 Btu/kwh, we find that the variable cost for conventional steam plants will be 1.8–2.7 mills/kwh.

TABLE 4—Nuclear Load Factors

Differential in variable costs (nuclear plant compared with fossil-fueled) (mills/kwh)	*Load factor*
0.0	60
−0.5	70
−1.0	75
−2.0	80

The Dresden Nuclear Power Station is expected to reach a fuel cost of about 2.5 mills/kwh in the mid-1960's on a set of assumptions that include fuel inventory charges at 4% and a 70% load factor. For this calculation we must subtract the in-pile fuel inventory charges. Making the adjustment, we find a variable fuel cost of 2.2 mills/kwh when fuel inventory is charged at 4% and 2.6 mills/kwh when fuel is charged at 14%. This is encouraging to the prospect of base loading of nuclear power plants, since there is reason to expect fuel fabrication costs, neutron economy and thermal efficiency will improve markedly in subsequent plants. Even for this first-generation water-moderated plant in which the full possibilities of neutron economy have not been realized, the "physics" part of fuel costs (burnup) is gratifyingly low (= 1.1 mills/kwh with Pu at $12/gm; = 1.9 mills/kwh on a throw-away basis).

Variable costs are by no means the entire story.§ Transmission costs tend to decrease the importance of fuel costs and increase the importance of local conditions. Down-time for refueling and maintenance will also tend to lower load factors somewhat—how much, the future will teach. Experience shows that the load factors of individual power plants decrease over the years as more efficient units are added to the network.

It is clear that the load factors of nuclear plants will depend heavily on technical progress and local conditions. Under the circumstances, it is perilous to generalize. Nevertheless for general studies, so long as nuclear power plants are a small fraction of total capability, Table 4 might be used as a first approximation. From the foregoing discussion, it is unlikely that these numbers are underestimates.

Conclusions

The national capital requirements for a nuclear power industry will be minimized if the proper types of reactor and fuel are chosen. This will be assured if proper factors are used in economic comparisons. These are:

1. Assessing capital charges at 12–15%.¶
2. Testing the effect of private ownership of fuels and special materials.
3. Using moderate load factors** as in Table 4.

In addition, consideration should be given to the amount of national capital required or existing in plants to produce nuclear fuels and special materials.

There has been some recent tendency to select reactor systems principally from the standpoint of their fuel cycle. It is, of course, easier to compare different fuel cycles than the probable trend of capital costs of different reactors. Nevertheless, it is essential to look beyond the fuel cycle to the entire reactor system, and behind the reactor to the whole nuclear economy. It is hoped that this study will focus attention on the larger picture.

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* The same consideration also applies to heavy water. Inventory charges will increase at a tempo that will depend on the popularity of heavy-water reactors.

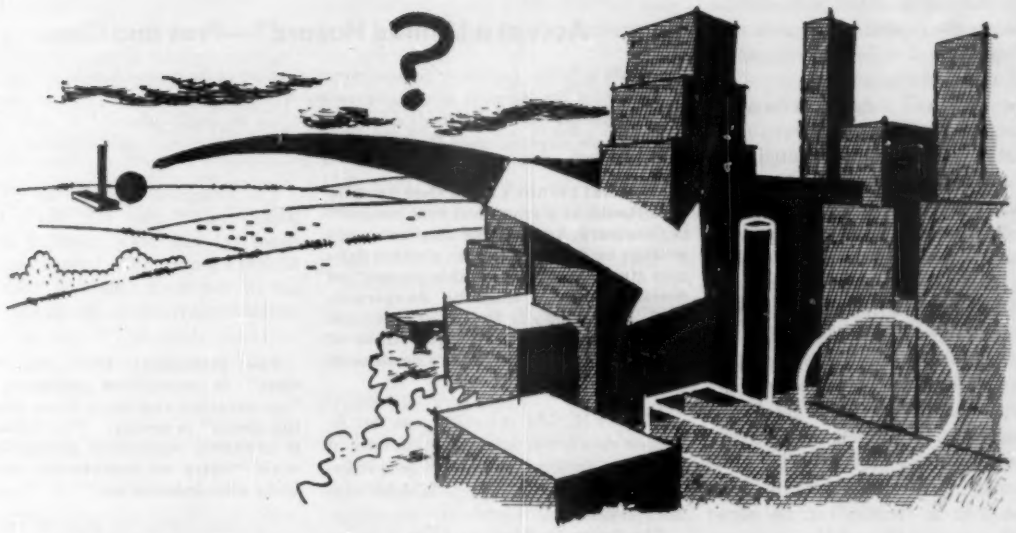
† Amortization is deducted. We have considered fuel as a depreciating asset and heavy water as a nondepreciating asset. The reasons for the distinction are not overwhelming. For economic comparisons the difference is not extremely important.

‡ That is, costs that occur only if the plant operates. The discussion is limited to the fuel part of the variable costs, which is perhaps 85% of the total.

§ I am indebted to W. W. Gartman for discussion of this point.

¶ Depending on the tax structure and local conditions, the range may be broader than this.

** Note that the Nuclear Power Group used 13.9% capital charge and 60% load factor in its analysis of the Homogeneous Reactor (NUCLEONICS, October, 1957, p. 69).



CAN WE BUILD REACTORS IN BIG CITIES? THE UNDERLYING QUESTION IS . . .

Reactor Exclusion Areas—Can They Be Eliminated?

Reactor safety, says the author, should depend on good engineering rather than exclusion. With conservative design we can put reactors where they are most useful without unusual public hazard

By G. W. C. TAIT
Atomic Energy of Canada Ltd., Chalk River, Ontario

REACTOR-SAFETY calculation is based on the assumption that an airborne cloud of fission products is formed at the reactor and dispersed to the nearby countryside. Most safety people calculate the maximum distance at which such a cloud can deliver an above-tolerance dose. Then they draw a circle with this radius about the reactor and use this circle as a guide in locating the reactor where people will not be unduly exposed to risk. The anomaly arises that the exclusion area is usually many times as large as the maximum area that could be threatened in a conceivable accident. This maximum threatened area is determined by the area and radioactivity content of the cloud rather than by the distance that it can travel.

Detailed examination of the predictions of cloud-dispersal theories suggests an alternative approach: rather than attempt to guarantee immunity to hazard by restriction of access to a huge exclusion area, it appears better to accept some degree of hazard strictly limited in magnitude. This approach has many precedents and is likely to be of much less harm to society than widespread restriction of the use of land.

Nature of Risk

The hazards of concern are those associated with dispersal of part of a reactor's contents in the form of an airborne cloud. They can be grouped under four major headings:

(a) Penetrating radiation from the passing cloud

(b) Entry of radiotoxins into the body with the inhaled air

(c) Penetrating radiation from deposits on the surface of the earth affecting those in the contaminated area

(d) Ingestion of radioactive deposits through the food chain

Three degrees of danger can be used to define zones of public concern (*1*):

A *lethal* zone associated predominantly with (a) and definable in terms of a cloud dosage of 400 curie-sec/m^3 (m = meter);

An *injury* zone arising from effects (b) and (c) and defined either by a cloud dosage of 10 curie-sec/m^3 or by a fallout concentration of 0.05 curie/m^2;

A *nuisance* zone due to (d), set by a fallout contamination of 10^{-3} curie/m^2. (Activities are measured in terms of standard fission products from long-irradiated fuel, 24 hr after irradiation.)

The maximum area that can be contaminated in a disaster can be computed in a straightforward manner by dividing the amount of released fission products by the tolerance level. For a basis of comparison we have made a study of a standard disaster using various theories and methods (*2*).

The consequence of the release of one megawatt-equivalent of long-irradiated reactor fuel as airborne material in the form of an instantaneous puff or cloud is examined. (A megawatt-equivalent is defined as the fission products in equilibrium with fuel producing 1 Mw of heat after 100-day irradiation and 24-hr decay. This is 8×10^5 curies.) It is assumed there are no buoyancy effects and the cloud remains on the surface of the earth.

Area Contamination

The area of actual hazard in any postulated disaster increases much less rapidly with unfavorable meteorological conditions than the area of the circle marked out by the limit of range. While the area in *jeopardy* of contamination to 0.05 curie/m^2 under commonly occurring inversion conditions can be thousands of square miles, the area *actually* contaminated cannot be more than $8 \times 10^5/0.05$ m^2 or 6.2 square miles under any conditions.

Allowing for areas contaminated more and less than 0.05 curie/m^2 the maximum area of the 0.05-curie/m^2 contour is considerably reduced and has been shown to be of the order of 0.4 square mile (*3*). Similarly the area of the 10-curie-sec/m^3 contour for breathing hazard is shown to range from 0.08 to 0.64 square miles as condi-

Accept a Limited Hazard?—Pros and Cons

(EDITOR'S NOTE: *In view of the controversial nature of the present article,* NUCLEONICS *submitted it for comment to a reactor-safety man of different views from the author's. His comments and the author's answers were not originally planned for publication, but we have prevailed upon them to permit it. Comments and answers follow.*)

COMMENT: While I agree that "public acceptance of a small but real hazard" is necessary, I think the author's suggestion to design into the plant a definite "maximum acceptable escape" of fission products may be dangerous. U. S. philosophy is that if one designs for no escape, with multiple lines of defense, one is still not sure because of lack of experience.

ANSWER: My intention was not to suggest that one should design for limited escape when complete retention is feasible. The point raised here is, I believe, more apparent than real.

The design problem as I see it is not so much concerned with disasters occurring from completely unforeseeable causes as with fairly well defined classes of accidents, the nature of which can be forecast with considerable confidence. It is agreed that when a potential cause of accident is noted, it should, when possible, be designed out of the system. However, in developing devices in new fields, one is always entering areas where knowledge is inadequate.

The efficient production of an aerosol cloud requires very definite conditions. These generally cannot be achieved in most types of reactors for any foreseeable disaster process.

Even assuming the principle is acceptable, I think the author's suggested limits are too high (not sufficiently conservative).

I accept that the opinion is a permissible one but do not see that there is a valid case for changing mine. However, I feel decisions in this matter are in the field of public policy or politics.

The author presents his basic health-physics and meteorological assumptions (page 73) very briefly and without adequate explanation or justification. I think they should be reviewed by a biologist.

With regard to the meteorological assumptions, the original report (*2*) dealt with this in much greater detail and was kindly commented on by senior research officers of both the British and the United States weather bureaus. Only minor suggestions were made by them, and these were in large part incorporated.

The biological assumptions are based largely on Marley and Fry's Geneva paper (*1*) and prior classified work by Marley's group. The hazard zone limits are in the main consistent with U. K. civil-defense recommendations.

The statement that the "lethal zone" is associated primarily with "penetrating radiation from the passing cloud" is wrong. The lethal zone is probably associated predominantly with "entry of radiotoxins into the body with inhaled air."

I cannot agree, at least in the sense that by lethality we refer to immediate deaths (within 6 months). In the inhalation zone there may be a few scattered deaths due to cancer, etc., after about 10 years but in general lethality can be prevented by simple controls (stay-in, evacuation, etc.).

The author dismisses much too lightly the possibility of release greater than 1 Mw. From other studies it appears this could be exceeded by two orders of magnitude.

The minimization of the likelihood of putting any large fraction of the reactor contents into an aerosol cloud traveling at surface level is based on a great many years' experience in aerosol studies.

The author's final numbers (*2*) representing death and injury are certainly low compared with other studies, and even appear low by about an order of magnitude in relation to areas of breathing hazard and lethal fallout given in this paper.

Although I agree my figures appear low beside many published, the differences are not marked if conditions of comparison are considered.

The reference to my own figures fails to take into account such evacuation as could reasonably be expected to take place with any kind of civil-defense organization or action by police or other public bodies. The essential point of the paper is not to set particular figures for permissible escape. Rather it is to suggest that if a reactor has been designed satisfactorily from this point of view, it can be placed, within wide limits, wherever it is most convenient.

tions vary from adiabatic lapse to moderate inversion.

The area within which injury or appreciable damage is likely to occur appears to be ~0.8 square miles per megawatt escape. Corresponding lethal areas are found to be of the order of 0.0004 square miles per megawatt for cloud passage and 0.002 square miles per megawatt from fallout in the first day.

Exclusion Distances

The calculation of the range of an airborne hazard is ultimately dependent on the basic atmospheric-diffusion theory developed by Sutton (*4*). The predictions are critically dependent on the diffusion parameters postulated, in particular the temperature gradient. As a result the validity and effect of any assumed "standard diffusion conditions" must be carefully examined. Let us consider the results of assuming a variety of standard conditions, in particular temperature inversions.

The range of lethal effects is small and can be passed over as insignificant in setting exclusion areas. There is some scatter among the various calculations but this is largely due to difficulties in handling all the physical considerations rather than to meteorology.

The injury zone for inhalation defined by a cloud dosage of 10 curie-sec/m³ is calculated to extend to 1.06 miles for our standard disaster under Harwell's standard meteorological conditions (adiabatic lapse and 5-m/sec wind speed).

Possibly the most detailed data on normal meteorological conditions are available for Oak Ridge (*4*), where adiabatic lapse, moderate inversion and strong inversion lead to predicted distances of extent for this hazard of 4.0, 6.9 and 50 miles, respectively. Chalk River estimates of likely meteorological conditions give ranges of 1.7–23 miles and Ann Arbor estimates, 0.45–12 miles (*5*).

The injury zone for external radiation from fallout defined by a fallout density of 0.05 curie/m² comes to 1.4 miles based on Harwell standard data. For moderate and strong inversions the distances become 3.2 and 8.2 miles. Harwell workers give a modified calculation for fallout in steady rain, increasing the distance to 3.2 miles under adiabatic conditions. However, an equally valid expression for fallout in sudden showers given by Holland (*6*) could increase the maximum extent of the 0.05-curie/m² zone to 35 miles in adiabatic conditions and 120 miles in inversions.

The nuisance zone or the limit of major agricultural restrictions is taken to be 10^{-3} curie/m². Marley and Fry give the corresponding distance as 11.3 miles (*1*). The distance under moderate stability conditions is 22 miles, and the recommended value for a light rain (< 1 mm/hr) is 31 miles.

Holland's formula for deposition by showers gives 325 miles for neutral conditions and 720 miles for a moderate inversion.

Probable Weather

Since such a wide range of predicted distances for extent of hazard appears from assuming a variety of meteorological conditions, it is necessary to consider the likelihood of the various conditions. Undue emphasis has been placed on the standard adiabatic condition largely because it is best suited to both experimental and theoretical study. In general, it represents a transition between day and night conditions, and near-adiabatic conditions persist only as a steady state with heavy cloud cover and marked winds. In contrast, inversion conditions occur nearly 50% of the time at most places.

Considering the prevalence of inversion states it is apparent that the limit of range of the damage zone under commonly occurring conditions will be an order of magnitude greater than predicted on the Harwell standard conditions. Under unusual conditions even greater travel must be anticipated. The original exclusion-area concept can have useful meaning only in terms of this damage zone.

Alternative Approach

The distance to which hazard can extend is critically dependent on meteorological conditions and can reach excessive values for commonly occurring weather situations. Yet the total hazard produced is definitely limited.

The maximum acceptable hazard should be reached by balancing its cost and likely frequency against the service provided by the reactor. This approach has many precedents and is likely to be of much less harm to society than widespread restriction of the use of land.

Public acceptance of a small but real hazard should not be too difficult if every reasonable effort is made to minimize it by conservative design and an honest appraisal of risk. The choice of 1-Mw escape serves as a realistic starting point. The consequences (0.0004 square miles of unavoidable lethality and 0.8 square miles of damage) are not too different from the hazard to persons dwelling on the site of a major aircraft crash. It is to be hoped that reactor disaster would be at most one tenth as frequent.

It is very doubtful that many types of reactors even in the 1,000-Mw range can achieve more than 1 Mw as airborne activity close to the ground. To disperse more than 1 Mw as an airborne cloud would normally require such heat as to lead to widespread dispersal of the cloud itself, beyond the range where the more serious concentrations could be achieved. A disaster design figure of 0.1–1.0-Mw release should therefore be quite practical for most reactors and attainable with some attention to design and containment for the most dangerous types.

Risk Policy

The final choice of acceptable hazard limits is of course a policy decision at the highest level. However, the following figures are suggested as a basis for consideration

	Maximum acceptable escape (Mw)	
Reactor type	*Builtup*	*Unsettled*
1,000-Mw(e) power	1	10
100-Mw(e) power	0.1	1
Experimental		0.1

It is important to retain a sense of proportion and realize that any possible reactor disaster lies well within the range of hazards to which the public is normally exposed.

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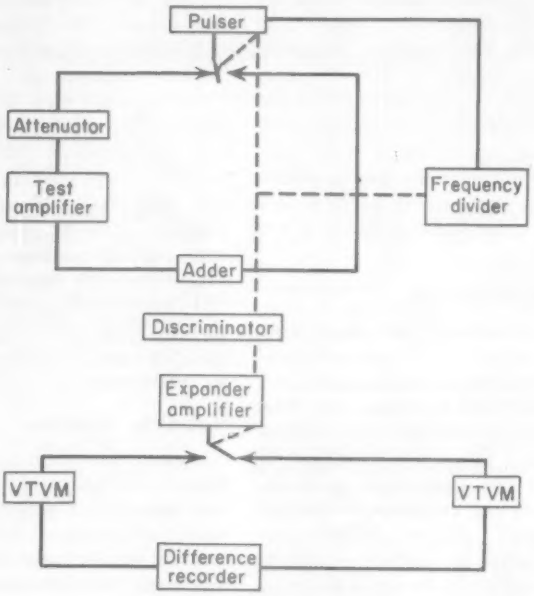

FIG. 1. Alternate input pulses go through attenuator-amplifier channel, remainder through reference channel. Recombined, they go through discriminator, expander, before being separated again for measurement by VTVM'S

Sensitive Measurement of Pulse-Amplifier Gain

By K. A. McCOLLOM, D. R. deBOISBLANC and J. B. THOMPSON
Phillips Petroleum Co., Idaho Falls, Idaho

Determining the long-term gain stability of pulse amplifiers for nuclear counters has been a problem for the amplifier designer for some time. This need has led us to design an amplifier comparator that not only checks gain stability to within 0.01% but also can be used for other purposes such as to compare the amplitude stability of two pulse generators to within 0.02%.

The comparator determines gain stability by comparing amplified pulses with attenuated pulses from the same source. Both pulse trains pass through a threshold device that subtracts the same voltage from each pulse and amplifies the remainder. The result is a very precise measurement of gain stability requiring only that the characteristics of a passive attenuator network remain constant.

By the use of this technique and suitable feedback control, an amplifier having extremely high pulse gain stability becomes possible.

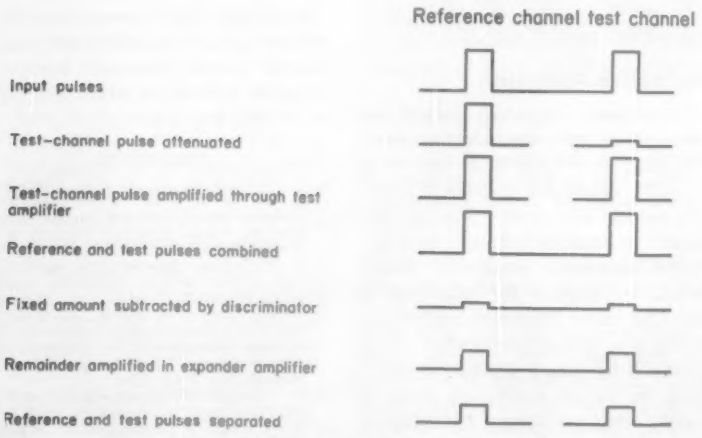
Reference channel test channel
Input pulses
Test-channel pulse attenuated
Test-channel pulse amplified through test amplifier
Reference and test pulses combined
Fixed amount subtracted by discriminator
Remainder amplified in expander amplifier
Reference and test pulses separated

FIG. 2. Wave forms demonstrate action of different sections of circuit. Output recorder indicates difference between pulse heights in two channels

Gain Measurement

Most linear-pulse-amplifier designs in common use today are more than five years old. At the time they were conceived, detectors were not sufficiently refined to require a gain stability of better than 0.1%. However, at the present time such a gain stability is insufficient for certain applications.

The immediate problem encountered is how to measure the gain accurately. The very nature of gain instabilities causes trouble in a device designed to measure them. The carefully designed amplifier has already used such design techniques as negative feedback and

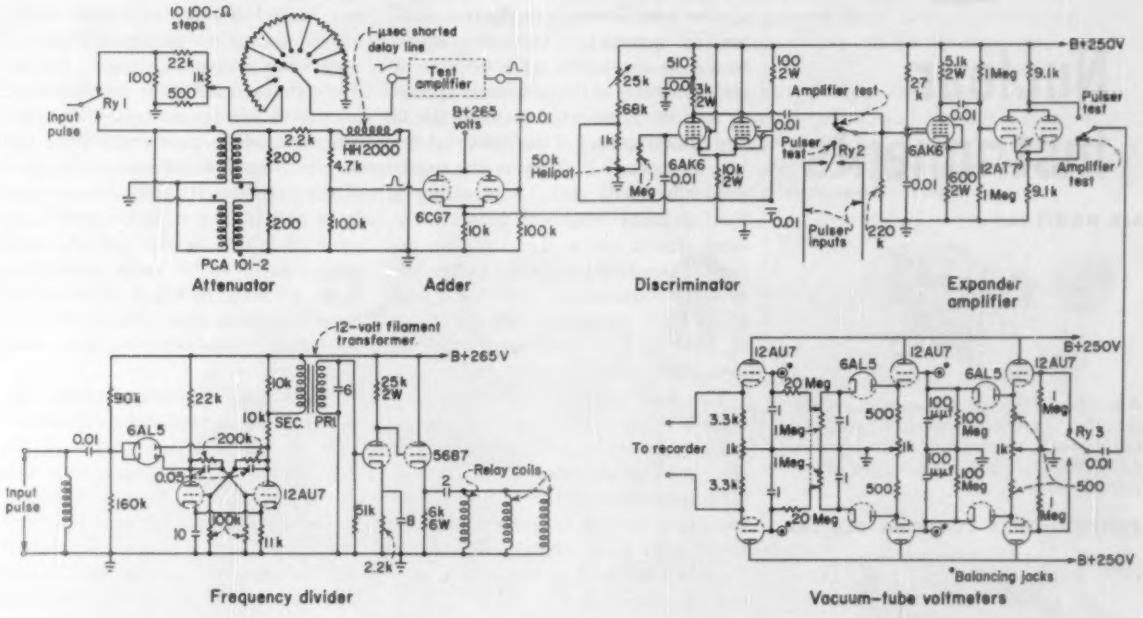

FIG. 3. Complete circuit diagram includes divider that operates channel-switching relay and alternative input for comparing two pulsers

temperature control to get the stability that can now be made available.

To measure gain reliably and speedily one should eliminate vacuum tubes from any part that affects the gain measurement. They are the active elements that cause instability.

Comparator Circuit

A block diagram of the comparator is shown in Fig. 1. A pulser performs three functions: providing an input pulse to the amplifier, a reference pulse around it and a signal to actuate a mercury relay that channels the pulses to their appropriate destinations. A divider produces half the frequency of the pulser for operation of the mercury switch. The switch then sends alternate pulses into the test-amplifier channel and every other pulse into the reference channel. After the pulses have passed the amplifier, they are inserted into a simple adding circuit. From this point they are operated on by the same units wherein vacuum-tube fluctuations do not disturb the comparative results since they have the same effect on pulses from both channels.

In a more recent version a delay line has been used to make two versions of the same pulse. These are compared instead of alternate pulses.

From the adding circuit the pulses pass through a standard pulse-amplitude discriminator that subtracts the same amount from each pulse. This discriminator is adjusted so that some small portion of the pulses, say 5%, is left beyond the discriminator. These pulses are then amplified in an expander amplifier. The remaining pulses are again divided into their separate channels by a second pole on the synchronously operated relay. Any changes in their height are then detected by peak-reading voltmeters in each channel. The output recorder takes the difference in the two readings. A change of 10.0% in the height of the pulse beyond the discriminator then corresponds to 0.5% change in the height of the original pulse.

The waveforms for various stages in the two channels can be seen in Fig. 2. As the pulses progress from top to bottom they are handled first in two channels, then in a common channel, then in two channels, and again in one channel. The complete basic circuit diagram is shown in Fig. 3.

Accuracy

Equations describing the behavior of the comparator are as follows

$$(P - D)A_{exp} - (PA_{att}A_{amp} - D)A_{exp} = \Delta V \quad (1)$$

$$A_{exp}P(1 - A_{att}A_{amp}) = \Delta V \quad (2)$$

Here A_{att} is the attenuation of the passive attenuator, A_{amp} is the amplification of the test amplifier, A_{exp} is the amplification of the expander amplifier, P is the pulser amplitude, and ΔV is the comparator output, which is proportional to amplifier-gain change.

The first portion of Eq. 1 corresponds to the reference channel and the second corresponds to the attenuation-amplification channel.

An important fact is that the setting of the discriminator does not enter into the value of ΔV. Thus, the long-term stability of the discriminator is not at all important to the accuracy of the measurement. Short-term stability might affect the measurement if the time constant of the peak-reading voltmeter were of the same order of magnitude as the instability in the discriminator.

If the discriminator were not used ahead of the expander amplifier, the

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accuracy requirements on the two peak-reading vacuum-tube voltmeters would be almost impossible. For instance, if the voltmeters at the end were required to read the differential between 516.33 and 515.00 instead of the difference between 16.33 and 15.00 the requirements would be very stiff. Subtracting a fixed quantity from both pulses in the same discriminator ahead of the expander amplifier relaxes the voltmeter-stability requirement from 0.002% to about 0.1% for gain-stability readings of 0.01%. The equations do not indicate this.

The final equation shows that the output voltage ΔV is proportional to both the pulse height and the gain of the expander amplifier, as well as the difference between the two channels. Putting numbers into this equation shows with what accuracy these must be controlled to obtain the accuracy desired in the system.

If the pulses from the two channels are exactly equal, change in either the expander-amplifier gain or the pulser amplitude cannot affect the output voltage since the term inside the parenthesis is zero. However, as the term inside the parenthesis departs from equality, the effects of the other two factors enter.

For example the change in ΔV from zero for a change in gain of 0.01% was calculated to be 0.05 volts when the pulser amplitude was 51 volts and the expander-amplifier gain was 10, some usual values for these constants. It was determined that when the change in gain was 0.25% the comparable ΔV was 1.33 volts.

The question was then posed as to how much the pulser amplitude or the expander-amplifier gain would have to vary when the amplifier gain has already changed 0.25% to be equivalent to 0.01% change in amplifier gain. The value of the pulser amplitude has to vary from 51 to 53 volts or the gain of the expander amplifier has to vary from 10.0 to 10.4 in order to give an error of 0.01% in the amplifier-gain measurement under these conditions. Thus, a change of 4% in either one of these constants gives 0.01% error in the gain measurement, for these conditions.

The only other source of error is the peak-reading vacuum-tube voltmeters. The two channels use halves of the same tubes for two stages, thus balancing out drifts due to filament-voltage changes. The result is a very stable voltmeter. In a 16-hr check of the vacuum-tube voltmeters alone there was no detectable drift on a recorder that could detect the equivalent of 0.003% amplifier-gain change.

The stability of the entire system except for the attenuator was checked by eliminating the attenuator and test amplifier and allowing both channels to operate as the reference channel does. The results show that the stability of the system including pulser, expander amplifier, discriminator and vacuum-tube voltmeters varied less than 0.02% in two hours. This is not the ultimate that can be had in stability. As was pointed out above, the expander amplifier and the pulser amplitude are probably the cause of the

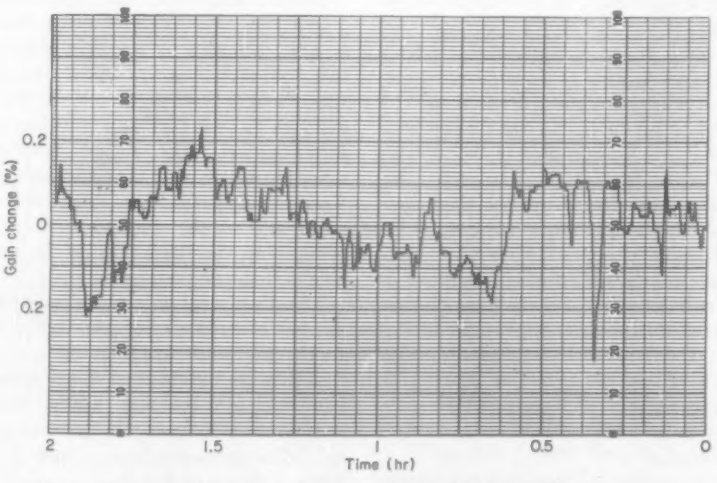

FIG. 4. Test result shows long-term gain stability of A1 amplifier

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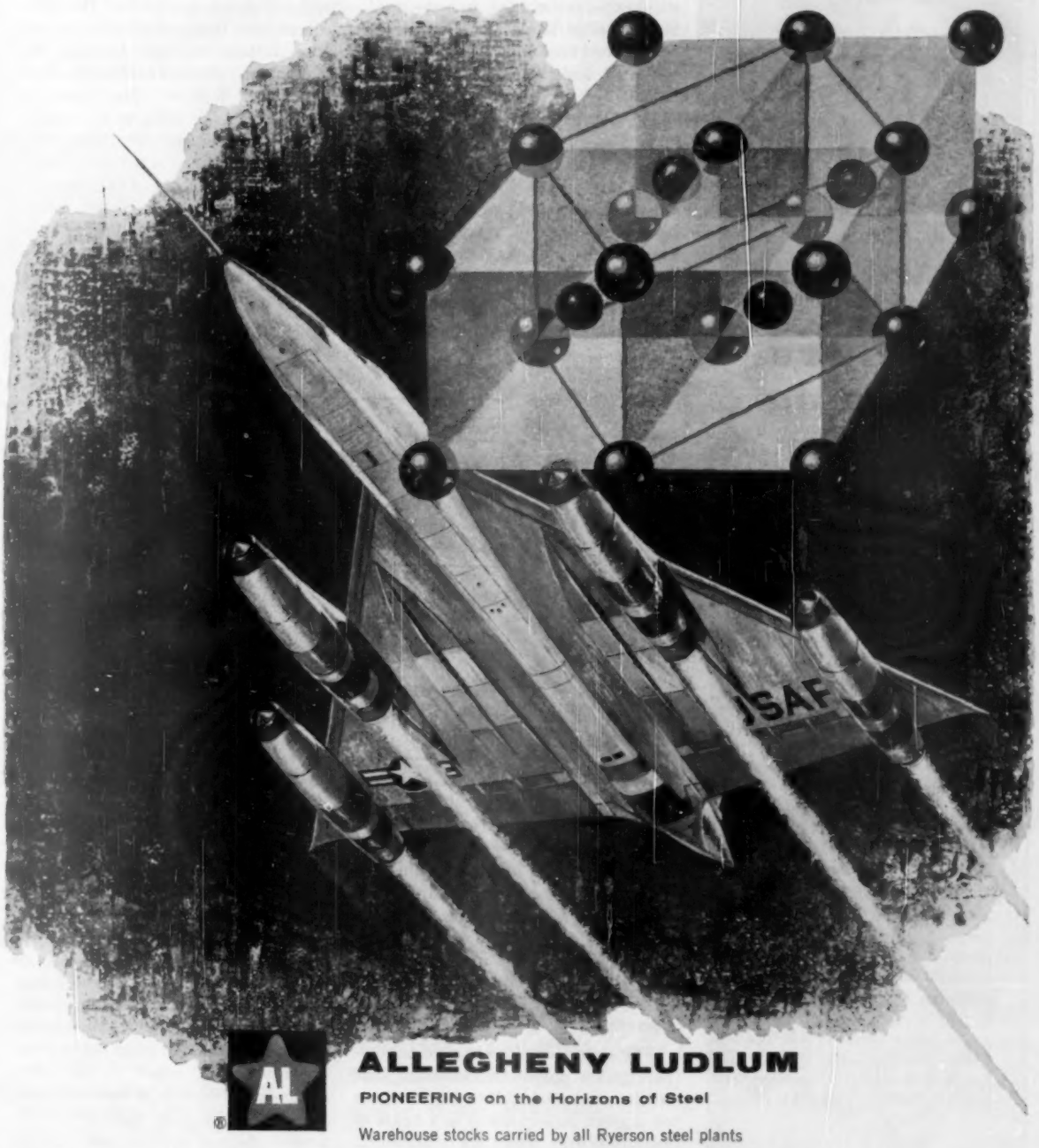

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drift and improvements can be made here. For this sensitivity, however, it is all the stability required.

Amplifier Tests

The record shown in Fig. 4 is a typical test result showing gain changes in an A1 amplifier. The testing of such amplifiers is the main purpose for which this instrument was designed. It is possible to push the sensitivity well beyond that shown here, which is 1% full scale, but this particular amplifier required this setting.

This record shows that over a 2-hr period the gain of this amplifier drifted 0.5%. The amplifier output was 15 volts. It should be pointed out that in a record like this occasional large excursions can be caused by line noise coupled into one channel and not the other. The amplifier channel is much more susceptible to line-noise pickup because of its system gain than is the other channel. Pickup in the early stages of the amplifier of course would be amplified along with the generator pulse and therefore would interfere.

Pulser Tests

The system can also be used to compare pulser amplitude stability. The result is not an absolute measurement on a given pulser, but it is a figure of amplitude drift, which is a combination of the stability of the two pulsers necessary to make this type of comparison. The two channels are used with a pulser working into each. The amount of drift indicates that the worst pulser can have no more than that drift.

Ultrastable Amplifier

The obvious next step after measuring gain stability is to use that information to make an ultrastable amplifier. A voltage proportional to the amplifier drift in gain can be used as a feedback signal to stabilize the gain. This requires that periodically a known pulse voltage be sent through the amplifier and through a reference channel and compared. The resulting signal is then fed back to a variable-gain amplifier stage. The pulse must not interfere to any great extent with the normal operations of the amplifier but must happen often enough to follow gain changes. In addition, the normal amplifier signals must not interfere with the pulse-signal indication for determination of gain stability.

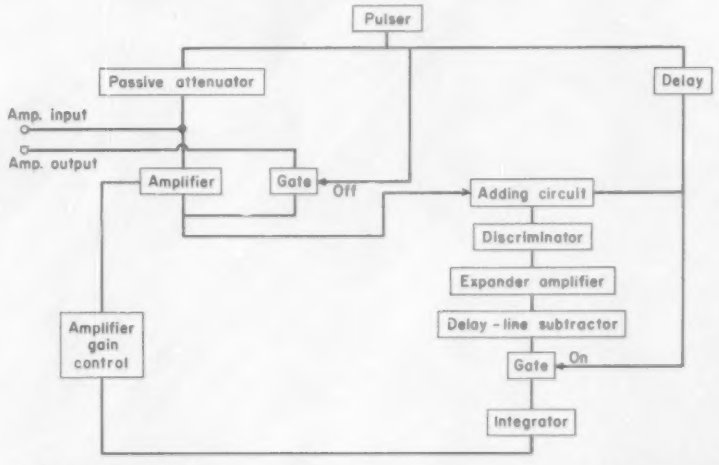

FIG. 5. Ultrastable pulse amplifier uses gain measurement to provide feedback signal that corrects any drift in gain

Such a system is shown in Fig. 5. Instead of the comparator switch system, a delay line is used to separate the same pulse for the two channels. This is an improvement since a single pulse is used instead of succeeding pulses. The most important contribution, however, is the removal of the switches from the input in normal operation. The result is an ultrastable amplifier with at least the prospect of 0.01% gain stability at the present stage of development. As refinements are made it is probable that a better gain stability can be obtained.

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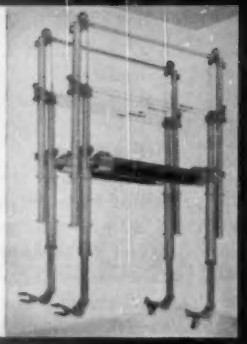

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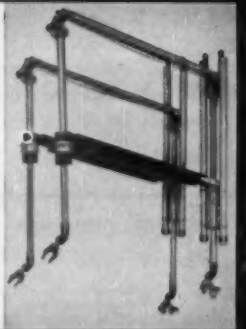

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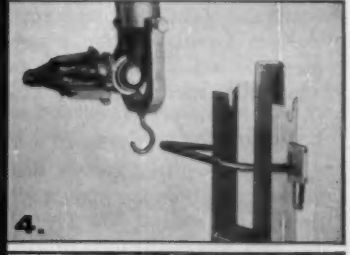

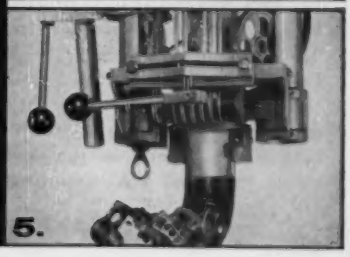

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Beta-Excited X-Ray Sources for Scintillation-Spectrometry Calibration

By JAMES G. KEREIAKES, G. R. KRAFT, O. E. WEIR and A. T. KREBS
Radiobiology Department
U. S. Army Medical Research Laboratory
Fort Knox, Kentucky

Low-energy gamma sources and beta-excited X-ray sources are finding considerable application in clinical (*1–12*) and industrial radiography (*1, 13, 14*), scintillation photometry (*15*), research (*1*), thickness gaging (*16*), etc. These uses have necessitated a better knowledge of the emitted radiation spectrum of these sources by scintillation-spectrometer methods.

The gamma and X-ray sources available for calibration of the low-energy spectrometer range (0–100 kev) are not numerous. The half-lives of calibration sources such as thulium-170 (129-day half-life) and xenon-133 (5.3-day half-life) are relatively short. In addition their gamma energies are fixed, thus requiring the use of several sources for a good calibration. An approach to the problem would be the use of the characteristic X-radiation excited by a pure beta emitter in various target foils. Here again some difficulty may remain in obtaining a sufficient number of materials in foil form to provide an extensive calibration.

This report presents a study on the use of various target materials in the form of metallic foils, free elements or compound salts as sources of beta-excited X-radiation for low-energy-range (0–100 kev) calibration in gamma scintillation spectrometry.

Experimental

Two beta-emitting sources (thallium-204 and strontium-90–yttrium-90) were used in this study. The Tl^{204} (4-year half-life) was in the form of $TlNO_3$ in HNO_3 solution and of 1-μc strength. The solution was evaporated on a Lucite planchet and covered by a very thin film of Mylar. The radiation emitted by this source is a 0.765-Mev beta ray produced in the decay to stable Pb^{204} and a K-capture process (*10, 17*).

The other source was a Sr^{90}-Y^{90} complex. Since no counting-source strengths of this isotope were on hand at the time of this study, this source was in the form of a Tracerlab Medical Applicator RA-25 with 5-mm active diameter and encapsulated in a protective cover of 2-mil stainless steel and 10-mil aluminum. The emitted radiation consists of the 0.537-Mev betas resulting from the decay of Sr^{90} to Y^{90} and 2.18-Mev betas produced in the decay of Y^{90} to stable zirconium. The beta particles emitted from this source have essentially the characteristic of a pure Y^{90} spectrum passed through 100 mg/cm² of filtration. The half-life of Sr^{90} is ~25 yr, that of Y^{90} ~62 hr.

The target materials are listed in the table. A small amount of the salts were compressed into disks, ½ in. in diameter and a few millimeters thick for easier handling (*18*). These disks were then placed over the source. A Lucite absorber of sufficient thickness to stop any beta particles that might be transmitted through the disks was placed between the disk and the phos-

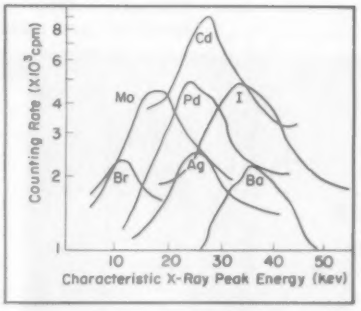

FIG. 1. Characteristic X-ray peaks produced in various target materials by thallium-204 betas

Target Materials—Calculated Characteristic X-ray Energies

Target material	*Excited X-ray*	$K_{\alpha_{avg}}$ *(A. U.)*	$E_{calc.}$ *(kev)*
Foils			
Tantalum	Ta	0.2173	57.3
Tin	Sn	0.4918	25.2
Lead	Pb	0.1676	74.1
Salts			
Ammonium molybdate	Mo	0.7099	17.6
Barium chloride	Ba	0.3866	32.1
Cadmium chloride	Cd	0.5360	23.2
Palladium chloride	Pd	0.5864	21.2
Potassium bromide	Br	1.0397	12.0
Silver chloride	Ag	0.5604	22.1
Sodium tungstate	W	0.2110	58.9
Thallous iodide	Tl	0.1722	72.1
Uranyl nitrate	U	0.1287	96.6
Other			
Iodine (crystalline)	I	0.4347	28.6

This article starts on p. 80

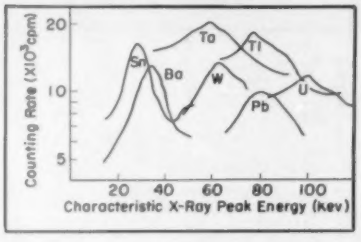

FIG. 2. Characteristic X-ray peaks produced in various materials by strontium-90–yttrium-90 betas

phor detector. Collimating lead plates placed in front of the Sr^{90}-Y^{90} source reduced the radiation intensity and provided a good statistical counting rate. The phosphor detector was a NaI(Tl) crystal, 1½ in. in diameter and 1 in. thick, to which we added a 3-mil Al window. The output of this tube was fed to a single-channel scintillation spectrometer. Operation conditions included a channel analyzer window width of 0.25 volt and a photomultiplier tube voltage of 1,000 volts. The signal-to-noise ratio for lower X-ray energies was 2,300/250 for Br and 4,500/200 for Mo.

Results and Discussion

The interaction of the source beta particles with the orbital electrons of the target material produces characteristic X-radiation of the target material. Figures 1 and 2 show the characteristic X-ray peaks excited in the various target materials by the Tl^{204} and Sr^{90}-Y^{90} beta particles. No attempt should be made to correlate the peak intensities, as various thicknesses of the foils and the disks were used.

The energy associated with the characteristic X-radiation produced by our sources was calculated, using as the wavelength the average K_α radiation for each material. The spectrometer pulse-height settings can then be plotted against the calculated X-ray peak energies. These data are shown in Fig. 3 and indicate the extensive calibration of the low-energy spectrometer range possible by this technique. The departure from linearity at the lower energies may be due to a crystal effect (*19*), i.e., nonlinearity in NaI response. Perhaps window thickness (even though it is only 3-mil Al in our study) becomes a factor at extremely low energies. This phenomenon requires further study.

(*Continued on p. 82.*)

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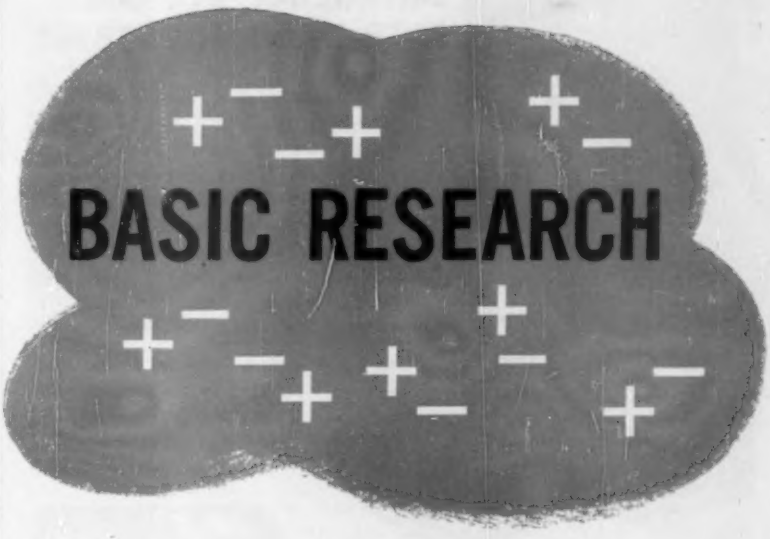

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CROSS SECTIONS

This article starts on p. 80

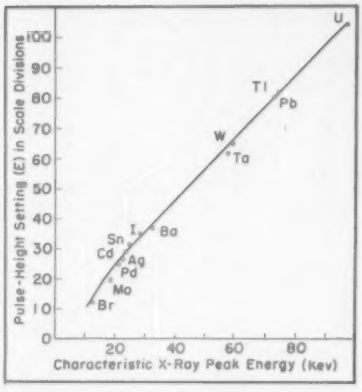

FIG. 3. Calibration curve for low-energy range of scintillation spectrometer using characteristic X-ray peaks produced by Tl^{204} and Sr^{90}-Y^{90} betas

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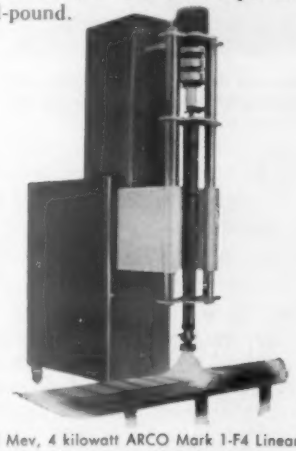

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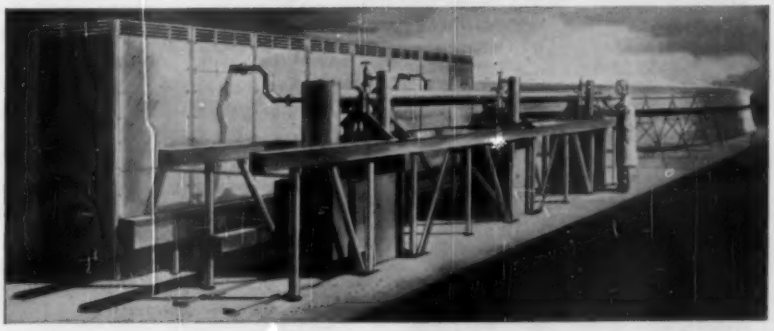

ARCO Building 20 Mev Linear Accelerator for M.I.T.—Harvard Synchrotron

A 20 Mev linear accelerator injector for the 6 Bev M.I.T.-Harvard synchrotron is now under construction by Applied Radiation Corporation.

The new ARCO accelerator provides 5 megawatts peak beam power, equalled by only a few accelerators in the world. It will allow the big M.I.T.-Harvard electron synchrotron to provide beam currents at an energy 6 times higher than today possible. To achieve high beam trapping efficiency required for this level of operation, unusually precise control of beam energy and frequency is mandatory.

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THERMONUCLEONICS

EDITOR'S NOTE: *This new department in* NUCLEONICS *will be devoted to the vital new subject of thermonuclear power. While political and administrative aspects will not normally be covered, a series of recent developments seemed to merit a report in the first item.*

Reduced Secrecy for Fusion Work?

Public confusion and uncertainty over the relative positions of the U. S. and British fusion efforts may have lead to a speeding up of declassification in this area. What happened was this: in spite of the fact that there has been close collaboration between British and U. S. researchers (see figure) British newspaper accounts said that results of the latest Harwell pinch-effect experiments (NU, Oct. '57, p. 21) were being withheld because of a U. S.-imposed "gag." R. A. Butler, leader of the House of Commons, added fuel to the fire with this statement, variously interpreted: "I have no reason to believe that we are not leading the world in the experiments we are making." In spite of official statements emphasizing the close cooperation and deploring comparisons, doubts persisted.

CLOSE COLLABORATION—(left to right) P. C. Thoneman and R. S. Pease of Harwell confer with Lyman Spitzer, head of Princeton University's Project Matterhorn during recent Sherwood meeting (NU, Nov. '57, p. 27)

Finally there has come the announcement that both countries will publish accounts of their recent fusion work "as early in the new year as the papers can be made ready." This apparently reflects a positive decision on proposals to liberalize classification that were up for Commission approval and promises freer discussion of the kind that has long been sought.

Toward Megagauss Magnetic Fields*

Containing an ionized plasma at temperatures of 100,000,000° C can only be done with strong magnetic fields. Thus it is not surprising that work at laboratories studying the control of thermonuclear reactions has included research on intense pulsed magnetic fields.

The fields are generated by discharging a bank of capacitors through a low-inductance high-current-capacity switch into magnetic circuits that range from single-turn coils to more complicated structures. Fields of over 1-million gauss can be generated for periods of a few microseconds. At these levels the energy density of the magnetic field compares with that of the most effective chemical explosives. The effects of such fields are correspondingly impressive: coil material is melted or caused to flow. Sometimes surprisingly clean incisions result from the "magnetic-saw effect" whereby a molten zone in the metal is propagated clear through as a result of the decreased viscosity and increased electrical resistivity of the zone. Coils can be designed so that the magnetic field is parallel to the current over much of their volume, thus eliminating some of these effects, but the fields thus produced are more costly in energy.

The important implication of all this is that magnetic fields can exert forces greater than those that hold metals together, and this makes the concept of a magnetic bottle to contain plasmas a much more reasonable one.

* Based on H. P. Furth, M. A. Levine, *Rev. Sci. Instr.* **28**, 949 (1957).

NUCLEAR ENGINEERING NOTES

New Capture Gamma Ray Measurements Every reactor physicist with any ambition at all has found his schemes frustrated more than once by the realization that there are whole groups of nuclear properties that have yet to be completely tied down by experiment. Capture-gamma-ray energies for the various nuclides are among these.*

A firm step forward in filling in our knowledge of capture gammas has been reported by R. W. Kenney and J. T. Mattingly† from the University of California Radiation Laboratory, Livermore, California. Kenney and Mattingly have measured the prompt-gamma-ray spectrum from thermal-neutron capture in U^{238}. Their experimental setup was sensitive to gamma-ray energies greater than 2 Mev. The results are summarized in the table. Three different prompt gamma energies were found, having a combined production cross section of 1.6 barns. The difference between this and the total neutron capture cross section of 2.7 barns is attributed to unobserved prompt gammas below 2 Mev.

Experimental arrangement. The general approach consisted of placing a moderately thin target of U^{238} metal in a beam of thermal neutrons and observing the gamma rays emitted by the target during the bombardment. The thermal neutron beam was supplied by the horizontal thermal column of the Livermore Water Boiler Neutron Source.

Prompt Gamma Rays from U^{238}

Gamma energy (Mev)	$\sigma_{n,\gamma}$ *(barns)*
4.0 ± 0.1	1.3 ± 0.3
5.9 ± 0.1	0.2 ± 0.07
7.5 ± 0.2	0.1 ± 0.03
Total contribution	1.6
Known total cross section	2.7
Difference (unresolved gammas below 2 Mev)	1.1

The target consisted of uranium so highly depleted in U^{235} that the gamma rays resulting from neutron capture or fission in the residual U^{235} were negligible. It was assumed that all observed gamma rays arose from the reaction $U^{238}(n,\gamma)U^{239}$. The detector was a conventional three-crystal scintillation pair spectrometer.

A gamma photon was detected by observing a triple coincidence among the three crystals. This event indicated that the photon had created a pair in the center crystal, that the positron had then annihilated in that crystal, and finally that the two annihilation gamma photons were detected by the two side crystals. Under these conditions the pulse height from the center crystal is proportional to $E = 1.02$ Mev, assuming that both pair fragments stop in the center crystal without losing energy by radiation. Observations of the pulse-height spectrum were made both by time-exposure photographic technique and by electronic pulse-height analysis. The energy scale and the spectrometer absolute efficiency were determined by using the 4.4-Mev gamma ray emitted by a Po-Be source of known activity.

The intensities of the three gamma lines were measured relative to the Cu^{63} line (7.7 Mev), which was also observed in the same geometry. Absolute cross sections for the three lines were calculated both from the known Cu^{63} cross section and the measured absolute efficiency of the spectrometer. The agreement was satisfactory.

The shape of the spectrum observed for the $U^{238}(n,\gamma)U^{239}$ reaction is typical of gamma spectra arising from thermal-neutron capture in heavy nuclei and corresponds to Mittelman's spectral class 2-b.

* For a summary of capture gamma rays see NUCLEONICS **13**, No. 5, 50 (1955).
† R. W. Kenney and J. T. Mattingly, UCRL-4735 (1956).

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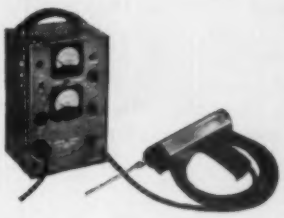

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When the second core is installed about 1960, the reactor will be able to run the turbogenerators at their maximum output of 100,000 kw.

The plant's cost to date, according to latest authoritative figures, is made up of $55-million construction cost including $13-million for the first core (to this total Duquesne contributed $5-million and Westinghouse $500,000), plus $15-million for the turbogenerator end of the plant from Duquesne, and $40–50-million AEC research-development funds, bringing the total to $110–120-million.

GATHERED IN CONTROL room on historic occasion when PWR first went critical are officials and key employees of AEC, Westinghouse and Duquesne Light Co., who collaborated to build plant. Seated dead center (white shirt) is Rear Adm. H. G. Rickover of AEC, who supervised construction; standing behind his right shoulder (white shirt) is Joseph C. Rengel, project manager for Westinghouse. To right of Rengel is John Gray, nuclear superintendent for Duquesne; on Rengel's left are Milton Shaw of the Commission; John Simpson, manager of Westinghouse's Bettis Labs, and Charles H. Weaver, Westinghouse vice-president for nuclear activities. Seated at reactor control (bottom right, white shirt) is H. C. Bixbe.

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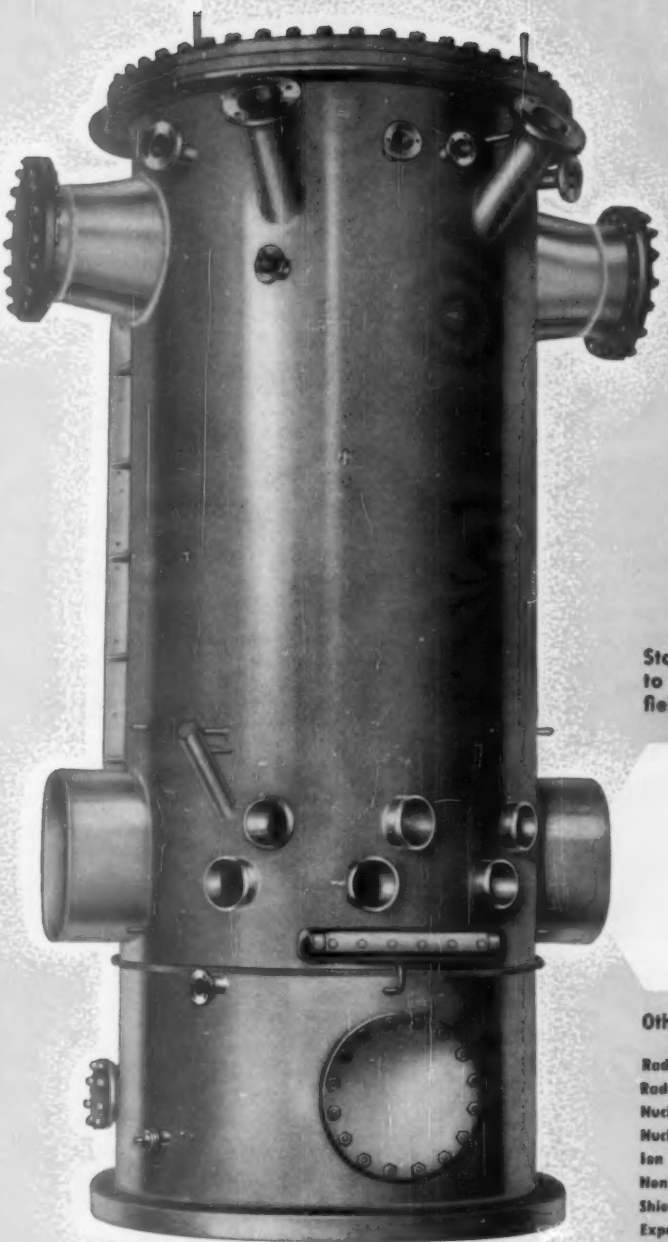

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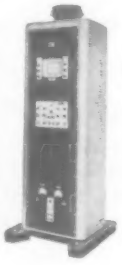

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Electrical Analog Solves Reactor Design Problems

By SHIGEO NAGAO
Tohoku University, Sendai, Japan

Reactor design invariably involves finding solutions to differential equations of the diffusion type, for example the neutron diffusion equation, the thermal conductivity equation, or the Fermi age equation. It often happens, especially for inhomogeneous reactors, that the geometry is too complex to permit analytical solutions. I would like to describe a simple method of using an electrical analog to find two-dimensional solutions of the above equations for geometries of arbitrary complexity. The analog surface is a resistive film that forms one plate of a wide parallel-plate condenser. An alternating voltage is fed in at appropriate source points on the resistive film causing a charging current to flow through the film. The voltage distribution throughout the film is then analogous to the spatial distribution of the dependent variable.

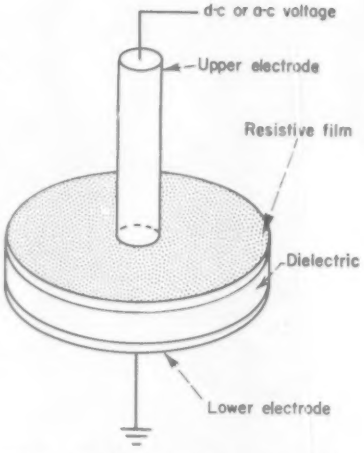

FIG. 1. Simple illustration of analog principle. Propagation of voltage from upper electrode over resistive film surface is governed by differential equations also used in heat transfer and neutron diffusion

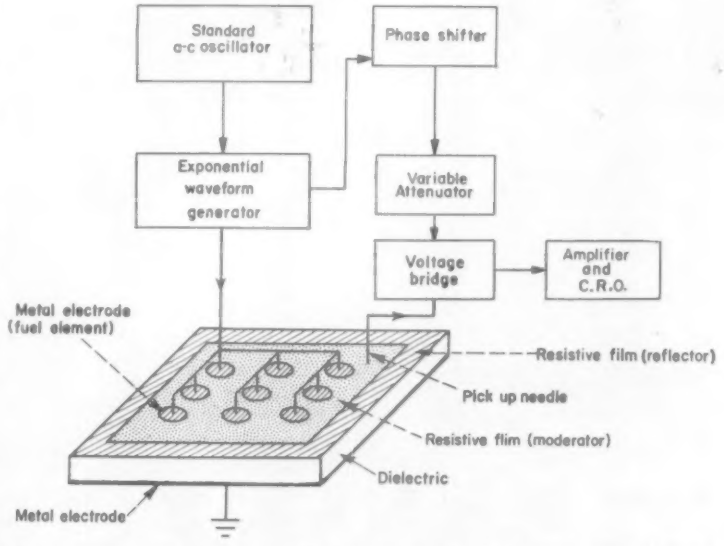

FIG. 2. Analog setup showing mockup of heterogeneous system and suggested external circuitry. Saw-tooth generator must have provision for varying time constant of exponential wave form

Basic Principles

A simple example will serve to illustrate the basic principle of the analog. Consider a circular parallel-plate condenser with a single axial voltage source as shown in Fig. 1. If a certain d-c voltage is applied at the origin of the r-θ polar-coordinate system, the voltage will propagate out radially along the film as the condenser system is charged up by the radial flow of current through the film resistance. The voltage $V(r,t)$ and radial current $I(r,t)$ at radius r and time t are obtained by solving the following differential equations

$$\frac{\partial V}{\partial r} = -\frac{\rho}{2\pi}\frac{I}{r} \qquad \frac{1}{r}\frac{\partial I}{\partial r} = -2\pi C_0 \frac{\partial V}{\partial t}$$

Here ρ is the surface resistivity and C_0 the capacity per unit area of the condenser. By eliminating I between the two equations, we get

$$\frac{1}{C_0\rho}\left(\frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\frac{\partial V}{\partial r}\right) = \frac{\partial V}{\partial t} \qquad (1)$$

which is mathematically the same as that for thermal conduction, for instance, in a source-free material with thermal conductivity $\kappa = 1/C_0\rho$. It is physically obvious that in situations without azimuthal symmetry, Eq. 1 can be generalized to

$$\kappa\nabla^2 V = \frac{\partial V}{\partial t} \qquad (2)$$

where ∇^2 is the two-dimensional Laplacian. Equation 2 is a two-dimensional time-dependent form of the diffusion equation that is often encountered in heat transfer and reactor physics problems. If the time-dependent boundary conditions are known (as represented by the input voltages on the film) then the analog solution is had by measuring the voltage distribution on the film.

Steady-State Diffusion

Of particular interest is the application to steady-state neutron diffusion. If we put $V = \phi(r,\theta)\psi(t)$, then by the familiar method of separating variables we substitute in Eq. 2 to obtain

$$\nabla^2\phi + B^2\phi = 0 \qquad B^2 = \frac{1}{\tau\kappa} \qquad (3)$$

$$\frac{\partial\psi}{\partial t} + \frac{1}{\tau}\psi = 0 \qquad (4)$$

Equation 3 is identical with the neutron diffusion equation which gives the steady-state spatial distribution of neutron flux in many reactor physics problems. The solution of Eq. 4 is an

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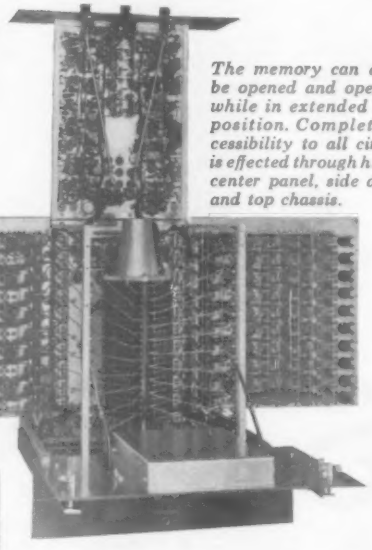

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*Average period of input blocking per analyzed pulse assuming a symmetrical spectrum.

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exponential with time constant $-\tau$. Thus if a voltage signal with a sawtooth exponential wave form is applied along the appropriate boundaries on the analog film, the distribution of peak voltage over the film will correspond to the spatial distribution of the neutron flux. The value of the constant B (which might, for instance, be the buckling for a reactor core) can be selected by adjusting the value of τ. For example, a 1-mm-thick glass plate with dielectric constant 10 and surface resistivity 10^5 ohms corresponds to

$$B = 1.05 \times 10^{-3}(\tau)^{-1/2}$$

Thus a whole range of B values can be covered by changing τ from several seconds to a few microseconds.

Spatial variations in B caused by two-dimensional variations in material composition can be mocked up by piecing together dielectrics with different strengths or films with different resistivity as shown in Fig. 2.

Figure 2 also indicates a possible instrumentation arrangement. Peak values of the voltage picked up by a needle electrode are measured by a voltage null method to avoid perturbations. Care should be taken to see that initial voltage transients have decayed before measurements are begun.

Recently I. Edamoto* has developed independently of the author a similar method for solving the torsion problem in a cylindrical body in which he used an electrolytic solution for the resistive film.

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* I. Edamoto, Techn. Rep. of Tohoku Univ., **21**, 51 (1956)

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How Channeling between Chunks Raises Neutron Transmission through Boral

By WALTER R. BURRUS*
Lockheed Aircraft Corp.
Marietta, Georgia

Boral is a mixture of boron carbide and aluminum encased between two thin layers of aluminum. Since boron carbide has a large $B^{10}(n,\alpha)Li^7$ cross section at thermal-neutron energies and the accompanying gamma ray is only 0.42 Mev, boral is valuable for use in nuclear shields where a large thermal flux must be absorbed without the production of hard gammas.

However, conventional calculations of the absorption of boral do not consider the channeling of neutrons through the spaces between the boron-carbide chunks. The results of a calculation for the transmission of ⅛-in. and ¼-in. boral that considers the channeling effect are in much better agreement with experimental data than earlier calculations neglecting channeling.

Calculation

The transmission of a slab consisting of randomly distributed chunks of average chord l (normally incident monoenergetic radiation) is given by

$$T = (1 - VF)^{t/l}$$

where T is fractional transmission, V is the volume fraction of the slab occupied by chunks, F is the average absorption of a single chunk, t is the thickness of the slab, and l is the average chord of a chunk.

The average transmission of one layer of the slab of thickness l is $1 - VF$. Since the chunks are assumed to be randomly placed, adjacent layers are statistically independent, and the overall transmission is the product of the transmission of t/l sublayers.

If the chunks are nearly spherical (*1*)

$$F = \frac{2}{(2r\Sigma)^2}\,[\tfrac{1}{2}(2r\Sigma)^2 - 1 + (1 + 2r\Sigma)e^{-2r\Sigma}]$$

where Σ is the linear attenuation coefficient of chunk material and r is the radius of a sphere (or equivalent radius on the basis of volume).

For a chunk of any shape without cavities a theorem due to Gauss states that the average chord l is given by $l = 4v/s$, where v is the volume of the chunk and s is its total surface area. For a sphere this gives $l = \frac{2}{3}r$.

If $VF \ll 1$, the transmission is approximately $T \approx e^{-Vt\Sigma F/l} \approx e^{-Vt\Sigma_{eff}}$. From the equations for F and l we can verify that for the limits of opaque and almost transparent chunks $\Sigma_{eff} = F/l \approx 1/l$ if $l\Sigma \gg 1$ and $\Sigma_{eff} = F/l \approx \Sigma$ if $l\Sigma \ll 1$. It should be noted that the effective linear attenuation coefficient for opaque chunks is $1/l$ and does not depend on Σ since all the trans-

TABLE 1—Size Distribution for B_4C Chunks

Mesh	*Average particle diameter (in.)*	$l\ (= \frac{2}{3}r)$ *(in.)*	*Volume fraction*
20–30	0.038	0.0253	17%
36–46	0.024	0.0160	11%
60–70	0.016	0.0107	6%
80–120	0.009	0.0060	6%

TABLE 2—Theoretical and Experimental Neutron Transmission through Boral *

Sample	*Neutron source*	*Detector*	*Experimental transmission*	*Channeling calculation*	*Conventional calculation*	*Ref.*
⅛-in. Alcoa (two samples)	Collimated beam from ORNL graphite reactor	Current detector (LiI xtal Cd difference)	7.0×10^{-3} ±40% (preliminary value)	9.6×10^{-3}	1.3×10^{-2}	*5*
¼-in. Alcoa	"	"	5.0×10^{-3} (preliminary value)	7.7×10^{-3}	4.8×10^{-4}	*9*
⅛-in. Brooks and Perkins	Water thermal column of ORNL graphite reactor	Thin indium foil	7.0×10^{-3}	2.7×10^{-3}	2.0×10^{-3}	*4*
⅛-in. ORNL	"	"	9.4×10^{-3}	2.7×10^{-3}	2.0×10^{-3}	*4*
¼-in. Brooks and Perkins	"	"	5.6×10^{-4}	1.7×10^{-3}	4.5×10^{-5}	*4*
¼-in. ORNL	"	"	7.6×10^{-4}	1.7×10^{-3}	4.5×10^{-5}	*4*

* Since the first two samples were measured with a different neutron source and detector, there is no direct comparison with the others.

* PRESENT ADDRESS: Physics Department, Ohio State University, Columbus, Ohio.

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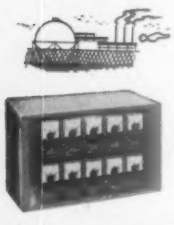

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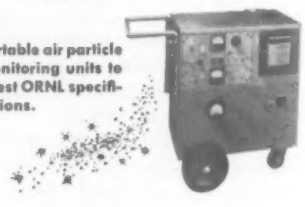

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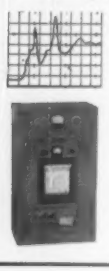

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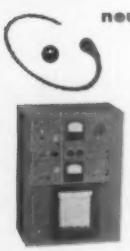

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mitted radiation channels around the chunks.

If the chunks consist of several groups with average chords $l_1, l_2, \ldots$ (and corresponding $V_1, V_2, \ldots, \Sigma_1, \Sigma_2, \ldots$), the transmission can be generalized to give $T \approx \exp - t\,(V_1{}^*\Sigma_{eff1} + V_2{}^*\Sigma_{eff2} + \ldots)$, where $V_i{}^* = V_i/(1 -$ volume fraction of all larger chunks). It is necessary to multiply V_i by $1/(1 -$ volume fraction of all larger chunks) to account for the crowding together of the smaller chunks by the larger ones.

This equation treats the distribution of chunks as if the chunks of various sizes were in separate layers. The result is always too small since it ignores voids that would be present in a layer if the larger chunks were separated out. Nevertheless, the result is correct for limiting cases of opaque and transparent chunks and is qualitatively correct in any case.

To calculate the transmission of ⅛-in. boral, it was assumed that the chunks of boron carbide were spherical. The size distribution shown in Table 1 is typical (*2*) of 20–100-mesh boron carbide usually used in boral. Other parameters used for the calculation are $\Sigma = 190.5$ in.$^{-1}$ at 2,200 m/sec (*3*) (neglecting attenuation in aluminum), $t = 0.085$ in. (not including aluminum cladding), $V = 40\%$ (not including aluminum cladding) $\approx 25\%$ over all.

The resulting transmission from the last equation is plotted against energy in Fig. 1. (It is assumed that Σ is proportional to 1/velocity.) The conventional calculation, assuming no channeling, is shown for comparison. Note that the transmission approaches the opaque-chunk limit at the low-energy end of the scale.

Since the chunks were assumed to be randomly distributed, there is no preferred direction for transmission. The transmission for neutrons incident at an angle θ with the normal can be found by replacing t by $t/\cos\theta$, the slant penetration. Figure 2 shows the transmission averaged over incident angles for an isotropic incident flux. Since transmitted neutron current in the forward direction is relatively greater than the isotropic flux, the average is carried out for both types of detectors. Figure 3 shows the results for ¼-in. boral.

A more extensive description of the method is given in an ORNL report now being published (*6*).

This article starts on p. 91

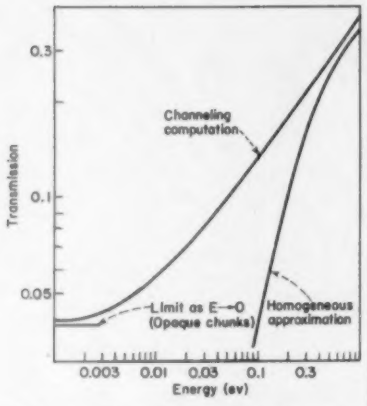

FIG. 1. Channeling computation departs from homogeneous approximation at low energies. Computations are for $\frac{1}{8}$-in. boral with typical 20–100-mesh B_4C distribution

Experimental Verification

Experiments performed to test boral have been gross-transmission measurements using various neutron detectors. It is possible to compare the results with calculations only if the angle and energy distribution of incident neutrons and the angle and energy sensitivity of the detector are known. The table on page 91 attempts to compare the calculations with several experiments performed at ORNL.

For the calculations it was assumed that the thermal-neutron spectrum was Maxwellian and that the angular distribution from the thermal column was of the Fermi type (*7*). Effective temperature of the neutrons was taken as room temperature, 293.6° K. The channeling calculations are an average of the results of Figs. 2 and 3 over the Maxwellian spectrum for the appropriate detector. The conventional calculations are based on the thermal-neutron absorption coefficients discussed by Zahn and Laporte (*8*). These coefficients take into account both spectrum hardening and angular listribution.

In the table the channeling calculation is too great in most cases by a factor of 2 or 3. The result of the conventional calculation is too small by more than a factor of 10 for $\frac{1}{4}$-in. samples.

A considerable difficulty in accurately comparing experiment and calculation is the lack of standardization of boral. After initial development, fabrication was standardized, but the ingot size, cladding thickness, fraction of boron carbide, and particle-size dis-

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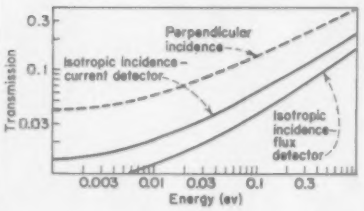

FIG. 2. Transmission of 1/8-in. boral with perpendicular incidence compared with current and flux from isotropic incidence

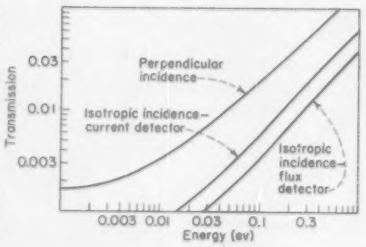

FIG. 3. Computations of Fig. 2 produce these results for 1/4-in. boral

tribution have not been rigorously fixed. In comparing experiments and calculations one must determine or guess the fractional weight of boron carbide, cladding thickness, and the size distribution.

* * *

This work was initiated at the Lid Tank Shielding Facility of the Oak Ridge National Laboratory while the author was on loan from the Wright Air Development Center Materials Laboratory. The author would like to acknowledge the assistance of R. W. Peelle and J. R. Smolen at ORNL and the cooperation of Alan Liebschutz at Lockheed and Stanley Szawlewicz at Wright Air Development Center. The basic method employed makes use of suggestions proposed by R. R. Coveyou and N. M. Smith at ORNL in 1947.

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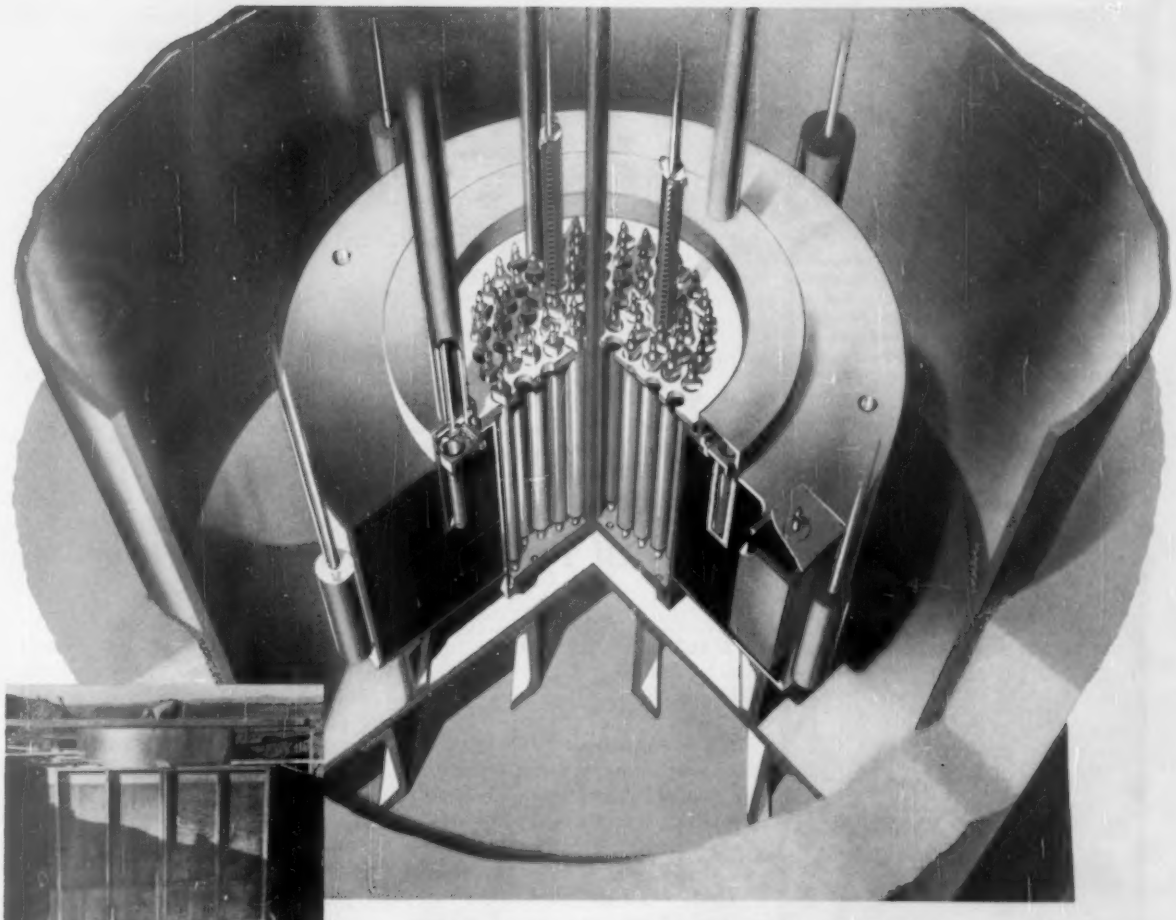

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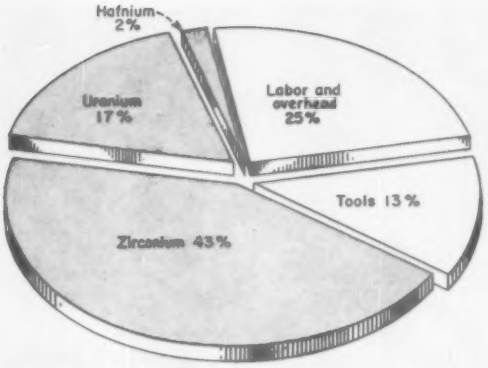

BREAKDOWN OF COST for fabricating first Shippingport core illustrates importance of materials costs—in this case, 62% of total. This, and similar situations for other cores, leads one to ask . . .

What Price Reactor Materials?

By MALCOLM F. JUDKINS
Firth Sterling Inc.
Pittsburgh, Pa.

The realization of competitive nuclear power rests, in large measure, on the cost of nuclear reactor materials. All too frequently, our freedom of choice in selecting reactor materials is so circumscribed as to be almost nonexistent. Few materials in use today possess all of the required nuclear, chemical, physical and mechanical properties. Those that come closest often are very costly. Several factors tend to make them costly: (a) some of them are rare and their low-grade ores are scattered widely in remote regions; (b) the winning of some materials from their ores involves complex extraction processes, frequently including the difficulty of separating chemical homologs or isotopes; (c) extremely high purity is required; usually only a few parts per million of contaminants are tolerable; (d) some materials are highly reactive.

The reactor designer must know what materials are available at what price. To meet this need, we have compiled a composite list of selected reactor materials showing the form in which they can be procured and the current price in that form. This information appears in the table.

Why So Much

It is instructive to look at a few reactor materials and see what makes them cost so much.

Niobium (Nb), which is an effective fuel-element alloy constituent, is, unfortunately, in limited supply. Nearly 95% of all niobium comes from Nigeria. Much of it is obtained as a by-product of tin mining. The outlook for large increases in the supply is unfavorable. The AEC arranged for delivery of approximately 30,000 lb during 1957. The estimated AEC requirements for 1958 are 40,000 lb and possibly 75,000 lb by 1959 or 1960.

Zirconium (Zr) is for the immediate present also in limited supply. Virtually all zirconium has been committed to the AEC since April of 1957. It is currently being produced at the rate of 625,000 lb/yr. Of this total, 325,000 lb is produced by Carborundum Metals and 300,000 lb by the U. S. Bureau of Mines at Albany, Ore., which has recently been reactivated by Wah Chang Corp. It is planned to expand this latter facility to 480,000 lb/yr. This is an interim contract until the new sponge plants under construction can assume the load. A contract for 1,000,000 lb/yr was awarded to U. S. Industrial Chemical Division of the National Distillers Corp., 700,000 lb to National Research Corp., and 500,000 lb additional to Carborundum.

Beryllium (Be) in its various forms can be purchased with AEC approval from Brush Beryllium Corp. and Beryllium Corp. The American Metal Market lists $71.50/lb for lump or beads f.o.b. Cleveland or Reading, Pa. On January 5, 1956, the AEC requested proposals for the production of up to 500,000 lb over a 5-yr period. One million pounds, or twice the amount requested, have been ordered from the

two sources above. The AEC plans to continue Be production at its Luckey, Ohio, plant until the new plants being built begin operating. Beryllium Corp. started limited production in mid-1957. Brush Beryllium Corp. plans starting production by mid-1958. As a result of production and fabrication savings consequent upon these large quantities, fabricated Be shapes may be reduced to $50–$100/lb.

Heavy water (D_2O) is also in limited supply. The costs in separating heavy water can be appreciated from the fact that natural water contains only 140–150 ppm of heavy water. Quantities required per reactor are frequently very large, 5–200 tons.

Helium (He) is definitely in short supply. The principal producing unit is the U. S. Bureau of Mines plant at Amarillo, Texas. Cylinder prices f.o.b. Buffalo range from $9.70 per 100 ft^3 for up to 2,000 ft^3 per month, to $7.70 per 100 ft^3 for 25,000 ft^3 per month.

Boron (B) occurs in nature as a mixture of isotopes B^{10} and B^{11} with relative abundance of 18.81% and 81.17% respectively. For a control-rod poison, the B^{10} is obviously greatly preferred because its neutron capture cross section is 4,000 barns compared to ~0.05 for B^{11}. To obtain a BF_3 complex in which 96% of the boron is B^{10}—an enrichment of 4.8 times normal—requires costly processing involving the difficulty of separating the isotopes.

Hafnium (Hf) in the form of crystal bars has been selling for a high price—when it was available. The title to all Hf, like Zr, now rests with the AEC. Considerable effort is being focused on extending the supply by using it in the form of a compound such as HfB_2.

Prices of Reactor Materials

Material	*Form*	*Price ($/lb)**	*Remarks*
Fuel and fertile materials			
Natural U	Forged billets	18.18	
U^{235}	Fluoride	5.62–17.07/gm	AEC price varies with enrichment (0.72–90%), is f.o.b. Oak Ridge
U^{233}	Nitrate	17/gm	
Pu^{239}	Ingot	12–45/gm	
Th^{232}	Ingot	19.52	AEC is stockpiling, will sell or lease until commercially available—maybe 1962
Diluents			
Al	2S sheet	0.43	
Nb	Melting stock	80–85	
	Powder	75–80	
Zr	Low Hf sponge	7.50	
	Low Hf and Zircaloy ingot	~15	
Moderators and reflectors			
Be	Lump or bead	71.50	
Be_2C	Powder	100	
BeO	Powder	10–20	
	Fabricated shapes	75–150	Price varies with design
Graphite	Extruded	0.50	Unmachined
D_2O	Liquid	28	Price in quantities of 125 lb or more, plus cost of container, is f.o.b. Savannah River
Polyphenyls	Powder	0.33–3.06/kg	
Coolants			
Bi	Ingot	2.25	In ton lots
He	Gas	0.085–0.105/ft^3	
Li	Hydride	11–14	
Na	Liquid	0.20	In tank-car quantities

* Unless otherwise noted.

Table continued on next page.

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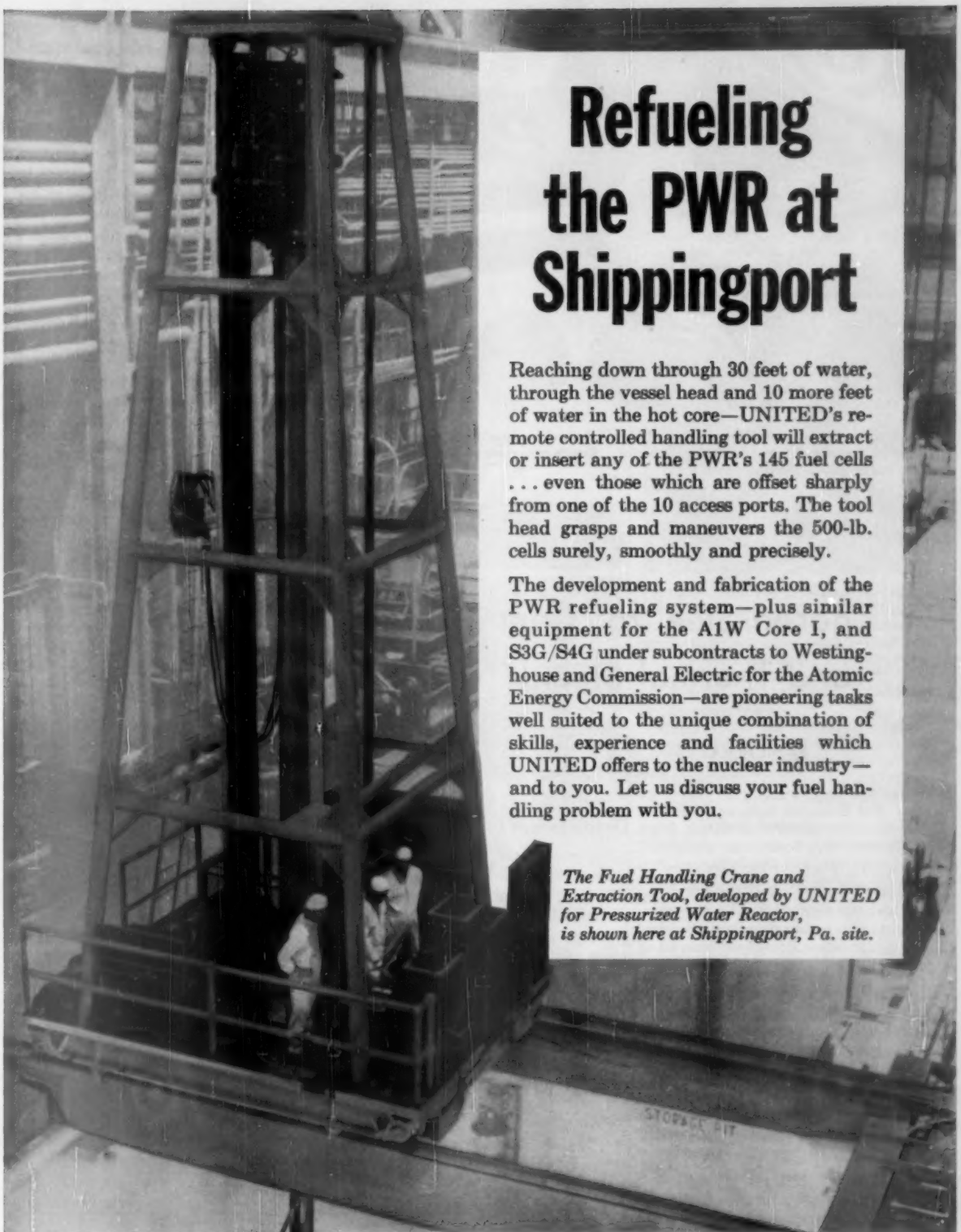
Prices of Reactor Materials (*Continued*)

Material	*Form*	*Price ($/lb)**	*Remarks*
Coolants (*cont.*)			
NaK	Liquid	0.65–1.75	Mixture is 44–78 wt% K; price varies with quantity (300,000–500 lb); is f.o.b. Evans City, Pa.
Pb	Pig	0.16	
Control rod poisons			
Natural B	Amorphous	13–70	Price varies with purity (90–99%)
	Crystalline	150	
BF_3	Liquid complex	3–6/gm	6.9% B of which 96% is B^{10}
B_4C	Powder	5.55–9.45	20–100 mesh; price varies with quantity (2,000–1 lb)
	Sintered cylinder	11.56	Compacted or extruded, ⅝ in. dia × 5 in.
B-steel	Sheet	3 and up	Stainless steel with 1½–2% B; price varies with size
	Wire	1.75–3	
Cd	Bars, sticks	1.70	
Dy, Er, Gd, Y	Powder	358.80	Ingot will be lower
Hf	Crystal bar	28	
Sm	Oxide	3.50–5/gm	Price varies with quantity (50–1 gm)
Cladding and structural materials			
Al	3003 sheet	0.60	
	3003 tubing	0.97	
Steel	Low carbon plate	0.51	Base price
	304L stainless strip, sheet	0.6325	
	321 stainless strip, sheet	0.655	
	347 stainless strip, sheet	0.7925	
Zr	Low-Hf and Zircaloy strip, sheet	23–30	
	Low Hf and Zircaloy welded tubing	45	
	Low Hf and Zircaloy seamless tubing	60	
Shielding			
Boral	⅛-in. sheet	8/ft²	Mixture of 65% Al and 35% B_4C clad with Al; price is f.o.b. Detroit
	¼-in. sheet	12/ft²	
	⅜-in. sheet	18/ft²	
Concrete	Ordinary	0.50/ft³	
	Installed	200/yd³	
	Barytes and magnetite	2–3/ft³	
	Steel punchings	5–20/ft³	
Heavy metal		8–12.50	Hot-pressed pieces, containing ~90% tungsten and balance of Ni and Cu, are up to 13 in. dia × 10 in. and 1,000 lb
Pb	Shot	0.30	
	Sheet	0.75	
Tungsten	Powder	~5	H_2 reduced (99% pure); price depends on ore price

* Unless otherwise noted.



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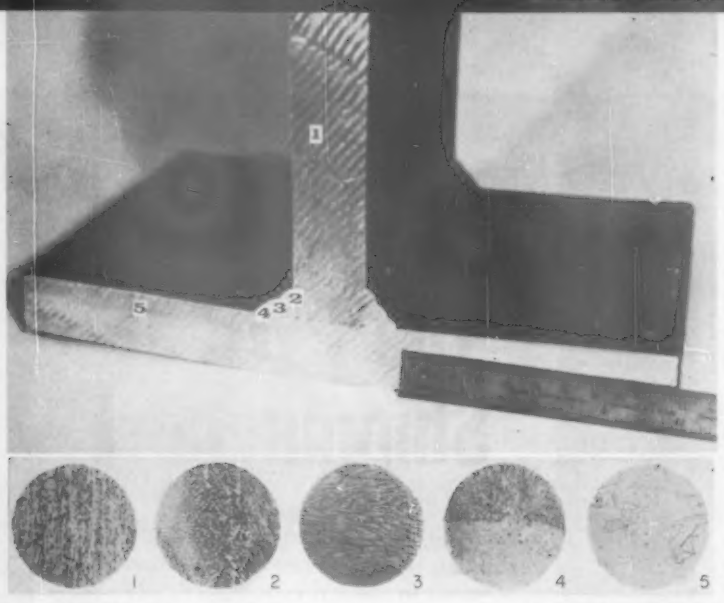

FIG. 1. Fillet weld joining 1-in. plates of 1 wt% B-steel (vertical) and type 304 stainless steel (horizontal) with type 308 weld metal. Results of metallographic examination show boron phase-alloying across weld

Boron Steel for Control Rods and Thermal Shields

By NICHOLAS BALAI
Argonne National Laboratory, Lemont, Illinois

Of the nine control rods in the EBWR, four have boron-steel absorber sections (the other five have hafnium). The thermal shield surrounding the core (and the shadow shields in front of the nozzle penetrations) is also of boron steel.

The advantages of using this material for control rods derive from its ready availability and relatively low cost ($3.40/lb). By contrast hafnium, when it is available, costs around $28/lb. These advantages, coupled with the fact that a B-steel rod will have somewhat greater blackness than a thermally black rod and is nearly as effective as a Hf rod (see Table 1), make the use of B-steel for this application very attractive.

The advantage of using B-steel for thermal shields derives from its ability to absorb neutrons with the consequent reduction in the formation of energetic capture gammas. Because of this, the diameter of the pressure vessel can be reduced by reducing the radial thickness required for the thermal shield.

Development of Specimens

It was assumed that a boron-alloyed, austenitic stainless steel offered a suitable starting point for the development of a high-boron alloy. The specimens prepared were alloys of natural boron, which contains 18.8% by weight of the B^{10} isotope, and type 304 (wrought) and CF-8 (cast) stainless steels.

Alloys containing up to 10 wt% of natural boron were prepared as castings. Air-melted castings containing up to 4 wt% B were found to be extremely notch-sensitive and brittle. Cast alloys containing 3 wt% B were not workable. It would appear that the metallic characteristics of the cast alloys vanish rapidly with increase in B content—the 9 and 10% alloys broke and rang like vitrified clay bricks.

A 10-in. × 56-in. cruciform-shaped casting containing 2 wt% B was produced and then machined. Radiographs revealed voids in the web (confirmed by sectioning) and inhomogeneity in the arms in addition to the obvious surface porosity. Additional work with castings was discontinued when tests to determine mechanical properties revealed a complete lack of ductility (see Table 2).

Wrought (rolled) specimens containing up to 2 wt% natural boron were also produced. The maximum amount of natural boron that can be tolerated by the type-304 stainless steel is in the vicinity of 2.2 wt%. This limit was established by the reduction of vacuum-melted 2-wt% B-steel ingots to plate and sheet products and by the shattering of a vacuum-melted 3-wt% B ingot. For air-melted materials, the limit is approximately 1.5 wt% of natural boron.

Weldability

Difficulty in welding was expected because of the low ductility of the 2-wt% B cast and wrought materials. A 75-deg double-"V" groove with a $\frac{1}{16}$-in.-wide land at the root in 1-in.-thick material was used in welding 15 test plates. Weld deposits from $\frac{1}{8}$-in., $\frac{5}{32}$-in. and $\frac{3}{16}$-in. electrodes were placed on alternate sides of the plates as dictated by bowing, i.e., a warped plate was straightened by welding on the opposite side of the groove.

TABLE 1—Burnup and Effectiveness of Hafnium and Boron-Steel Rods

Rod composition	*Thickness (in.)*	*Effectiveness* (%)*		*Percent burnup in 1 yr*
		Initial	*After 1 yr*	
1 wt% B-steel	¼	88	80	28.5
2 wt% B-steel	¼	109	104	14.5
3 wt% B-steel	¼	117	114	9.8
Hafnium	⅛	108	108	0

* Values are referred to a black thermal rod. Values >100% are due to absorption of epithermal flux. Average thermal neutron flux was 1.5×10^{13}.

TABLE 2—Typical Mechanical Properties of B-Steels

*Material**	*Tensile strength (psi)*	*Yield point (psi)*	*Reduction (%)*	*Elongation (%)*
2% B casting (horizontal cast plate)	51,200	30,200	0	0.9
2% B casting (edge cast plate)	41,200	28,800	1.0	0.8
1% B wrought (air-melted and cross-rolled)	38,800	—	1.0	0.8
	95,800(L)	54,700	13.0	18.0
	86,100(T)	56,500	15.0	17.0
1.2% B wrought (vacuum-melted)	74,100(L)	31,500	7.1	8.9
	81,800(T)	34,300	21.1	23.5
1.4% B wrought (air-melted)	92,200(L)	33,000	7.4	11.2
	98,200(T)	42,700	10.7	9.5
1.5% B wrought (vacuum-melted)	97,000(L)	37,600	13.8	14.6
	95,000(T)	42,000	13.0	11.2
2% B wrought (vacuum-melted)	101,000(L)	70,000	7.5	8.3
	98,200(T)	37,500	7.0	8.5

* All wrought materials were air-cooled from 1,900 or 1,950° F at the mill.

Titania-coated electrodes, in 308 and 310 compositions, did not fuse the roots of the welds, when lands were butted, and fissured on cooling. The fissuring was eliminated by using lime-coated electrodes. Fusion at the root of the weld was obtained by using wider lands (1/8 in.). Butt-weld joint efficiencies of 80% (based on tensile strength of type-304 end plates) in the as-welded condition were easily attained with deposited parallel stringer passes.

The ductility of the stainless-steel weld metal was found to be as low as that of the boron-containing base material. From the fine-grained appearance of the weld-metal fractures, it was suspected that the boron phase-alloyed across the weld in the welding process. The suspected alloying was confirmed metallographically from a sectioned "T" fillet weld between 304 and 304-1B (see Fig. 1).

FIG. 2. Obround slugs, 5 in. long, of 1 and 2 wt% B-steel after irradiation in flux of $1.5 \times 10^{21} nvt$ showed no cracking and only superficial hardening

Corrosion Resistance

The corrosion resistance of the 1 and 2 wt% natural boron stainless steel alloys, in both air- and vacuum-melted grades, is at least equal to that of the austenitic grade (type 304). Welds joining the alloys to each other and to SS304 are also corrosion resistant to the same degree.

Irradiation Resistance

Four slugs, each 5 in. long, were machined from 1-in. wrought plate of 1 and 2 wt% composition for a test irradiation in the MTR. Figure 2 shows their appearance after a cold irradiation exposure of $1.5 \times 10^{21} nvt$ (thermal neutrons). A dye-check inspection showed no cracking of the sides or ends. Hardness checks showed a superficial hardening comparable to that sustained by the austenitic material at the same exposure, i.e., 10–15 points on the Drale D scale. A more scientific irradiation, which includes tensile and notched impact specimens in base material and welds, is awaiting space in the MTR.

* * *

I wish to acknowledge the contributions of Dr. C. R. Breden, N. R. Grant, R. E. Bailey and H. Sommer for assessing the corrosion resistance of the alloys, obtaining the preliminary irradiation data, and melting-down the numerous types of electrodes used.

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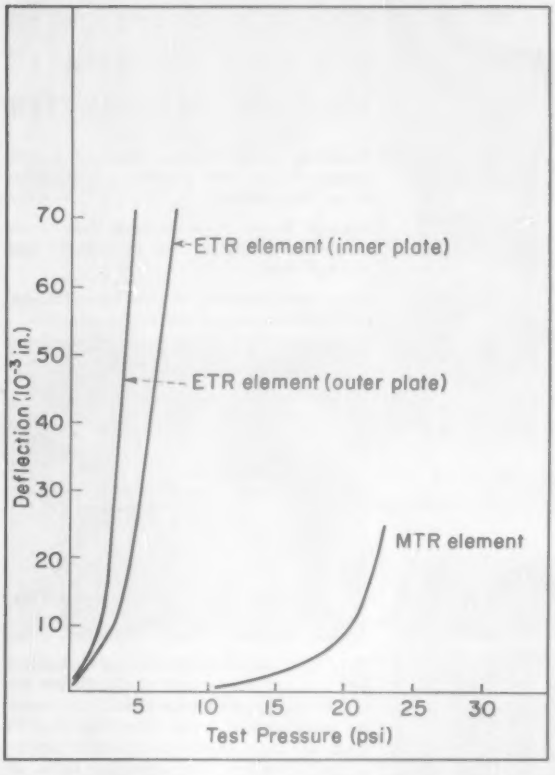

FIG. 1. Deflection of fuel element plates observed in bench test with static air pressure. ETR plates are compared with MTR plate

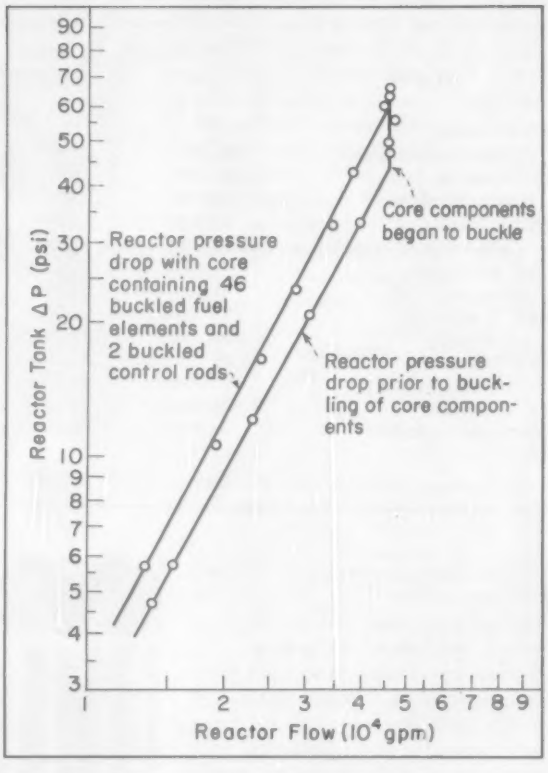

FIG. 2. In-pile flow test of core buckled fuel elements when flow reached full-power design value. Curves show change in ΔP

The Engineering Test Reactor —A Status Report*

By R. L. DOAN
Phillips Petroleum Co., Idaho Falls, Idaho

The Engineering Test Reactor (*1*) went critical at 10:59 p.m. on September 19, 1957, three weeks after the official termination of construction activities. This event was preceded by extensive preoperational tests of various reactor components and the coolant system. Low-power testing is now in progress involving equipment debugging, rod calibration, flux distribution measurements, void and temperature coefficient determinations, etc. Installation of major experimental facility loops in core positions will necessitate substantial reactor down time and subsequent careful study of the change in core conditions resulting therefrom. It will be several months before any large portion of the planned experimental program can get underway.

General plans for the Engineering Test Reactor call for bringing the reactor as rapidly as practicable up to the highest power that can be achieved safely with the present core components. The experimental test program will be started at this stage. Operation of the reactor at full design power must await the development of improved fuel elements and control rods. Work along this line is already underway.

It can be expected that any major nuclear reactor involving new design principles may initially fall somewhat short of expectations, and in this respect the ETR is no exception. I shall review some of the problems revealed by test work to date.

Fuel-Element Stability

The fuel elements for the ETR are the flat-plate type, each assembly consisting of 19 plates 0.050 in. thick separated by channels through which the light water coolant flows at a design rate of 35 ft/sec. The plates are approximately 3 in. wide and 36 in. long. The fuel is highly enriched uranium alloyed with aluminum and clad with aluminum. Boron uniformly distrib-

* Based on a paper 57-AIF-2 presented at the fourth annual Atomic Industrial Forum conference, October 28–31, 1957.

uted throughout the fuel section provides a burnable poison that helps to keep the neutron flux reasonably uniform throughout the core for the entire fuel cycle.

One sometimes hears the term "MTR-type" applied to ETR fuel elements. This is quite misleading since the only similarity between MTR and ETR fuel elements is that they both have the same number of plates of the same width and thickness except for the outer fuel plates which are 0.050 in. for the ETR and 0.0625 in. for the MTR. There is an important difference between the curved plates of the MTR and the flat ones of the ETR, that gives rise to a major obstacle to full-scale ETR operation. Two other significant differences are the 50% greater length of the fuel sections in the ETR fuel elements as compared to the MTR (36 in. vs 24 in.) and the presence of distributed boron in the ETR element.

Several problems have been encountered in the preoperational testing of the fuel elements and control rods and will be discussed separately. The first, and most important, has to do with the mechanical strength of the fuel element structure, which is not great enough to withstand the hydraulic stresses under full design coolant flow rates.

It is clearly of first importance to determine, insofar as can be done in advance of actual operation, the probable integrity of the various core components under the total load of mechanical and thermal stresses that will be encountered at design power. The best that can be done in this direction is to measure the response of the core components to mechanical stresses of various magnitudes under room-temperature conditions and try to extrapolate to the operating temperature conditions. Such investigations have been made on both ETR fuel elements and ETR control rods using specially designed static and hydraulic flow test facilities and also the primary coolant system of the reactor itself. The results are not encouraging from the viewpoint of full-power operation with the present core components.

Pre-reactor stress tests on ETR fuel elements consisted of both static pressure tests and flow tests. The former were carried out by applying air pressure to the inside of the element and measuring the deflection of the outside fuel plates. The results on two typical fuel elements are shown in Fig. 1, together with an MTR fuel element for comparison purposes. It will be noted that the 0.050 in. ETR flat plate deflects much more at a given pressure differential than does the 0.0625 in. MTR curved plate. A 21-psi pressure differential is required to bring about a 10-mil deflection in the MTR plate, while only 2.5 psi is required for the ETR plate. It is not expected that the two values should be the same but the very low value for the ETR flat-plate element does underline its structural weakness. Under operating conditions fuel-plate deflection should be negligible, certainly less than 10 mils. This places an upper limit of something like 2.5 psi on the pressure differential for the ETR fuel element even at room-temperature conditions. The low strength of the plates, plus the apparent lack of flatness of several of them, gave an early indication that some of the plates might buckle and collapse at high flow rates. This was confirmed by the pre-reactor hydraulic flow tests, which collapsed the fuel plates at flow rates in the range of 33–35 ft/sec. Design flow rate at full power operation is 35 ft/sec, although there is some indication that the actual average requirement may be somewhat lower than this.

The out-of-reactor flow tests were made in a nine-element hydraulic rig designed and constructed by the General Electric Co. for use in their core development studies during the ETR design and later transferred to Phillips. As many as five fuel elements can be tested at one time up to flow rates 25% higher than design coolant flow in the reactor. The pumping capacity is 6,000 gpm at a 160 ft head. System flow is measured with a venturi nozzle and mercury manometer. Mercury manometers and pressure test gauges are employed for obtaining pressures and pressure differentials. Observations are made of flow rate vs pressure drop across the fuel elements.

Similar measurements have been made in the reactor itself using the primary coolant system as the hydraulic test loop at normal operating pressure (200 psi).

The general results of the hydraulic flow tests both in the hydraulic test facility and in the reactor were as follows: (a) A variation in flow rate of as much as 25% was observed between different channels; (b) The fuel assemblies buckled at an average channel velocity of 33–35 ft/sec in the hydraulic test facility and 30 ft/sec in the reactor; (c) The over-all water balance on the reactor indicates that it would take about 55,000 gpm at a 52-psi pressure differential (ΔP) to give an average flow of 35 ft/sec in the (undistorted) fuel channels for a core loading of 49 fuel assemblies, 16 control rods and 31 core filler pieces. The estimated design flow rate for this loading is about 49,000 gpm and the core ΔP about 42 psi.

Figure 2 gives a typical plot of total reactor flow vs ΔP prior to and following the buckling of the fuel elements. The buckling started at a ΔP of about 45 psi. Collapse of the plates restricted the flow in a large number of channels, with a resultant increase in ΔP for any given flow rate. Figure 3

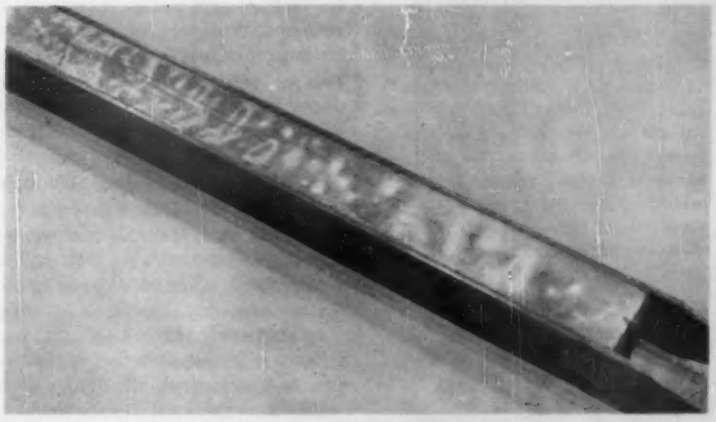

FIG. 3. One of ETR fuel elements that buckled during in-core test at design flow

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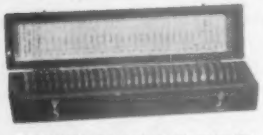

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NUCLEAR ENGINEERING

This article starts on p. 102

is a photograph of a fuel element after hydraulic test to failure, showing a buckled fuel plate.

In view of the hydraulic test results showing collapse of the fuel elements at an average flow velocity of 30 ft/sec at room temperature, the question arises as to the maximum safe flow, and hence the maximum safe power of the reactor under operating conditions. This is a difficult question to answer in the absence of detailed knowledge of thermal stress effects at elevated plate temperatures. Based partly on a desire to retain a certain factor of safety for the fuel elements and partly on the necessity of imposing an upper limit on reactor power because of inadequate cooling of the fuel section of the control rods to be described later, it has been decided to limit the maximum flow rate under operating conditions to 18 ft/sec, and the maximum reactor power to 90 Mw. If new information should become available during the power runs indicating that these limitations are unjustifiably restrictive, they will be reconsidered. The same thing applies to lowering the limits. At present they are merely target estimates.

Since it is clear that the reactor cannot be operated at full design power with the present flat-plate fuel elements, several alternative designs have been considered:

- Perforating the side plates to relieve the pressure differential between channels. Preliminary hydraulic flow tests on fuel elements having slotted side plates reveal little or no plate distortion up to 25% above design flow rate.

- General Electric has developed a roll-swage cold-fabrication technique that leaves the fuel plates in a hardened condition. Room-temperature hydraulic flow tests show no significant distortion up to flow rates 25% higher than the design value.

- Redesign of the ETR fuel element to provide a central support for the plates along the lines of SPERT (*2*) fuel elements would probably yield a satisfactory fuel element. But this is an expensive modification and perhaps the least desirable of the three alternatives.

Much testing and analytical work remains to be done before any of the foregoing, or other, alternatives can be accepted for full-power operation. The slotted side plates, for example, will probably solve the pressure-differential problem but may introduce some other problems of flow distribution across the plates that will give trouble. Likewise, the cold-worked fuel elements, although satisfactorily withstanding the hydraulic stresses of full design flow at room temperatures, could quite possibly collapse under the combined load of hydraulic and thermal stresses at the maximum temperatures encountered under full-scale reactor operations.

Reactivity Measurements

The fuel section of the ETR fuel elements is an alloy of U^{235}, boron and aluminum. The specifications call for 255 gm of U^{235} and 1.6 gm of boron in some of the fuel elements and 239 gm of U^{235} and 2.5 gm of boron in others. This fuel-and-boron loading is calculated to give an excess reactivity of approximately 11% when 49 fuel elements of the first category are loaded into the reactor with the full complement of 31 aluminum filler pieces in the core experimental facilities.

To verify the correctness of this and other reactor calculations, particularly those associated with the experimental program, an ETR critical assembly has been built and placed in operation in a pool of water adjacent to the reactor building. The ETRC is a fullscale core prototype of the ETR. The internals of the core, such as fuel elements and control rods, are actual ETR components except for the poison section of the control rods, which are cadmium in the ETRC and boron-stainless steel alloy in the ETR.

The general results obtained to date on the ETRC may be summarized as follows:

- The average worth of the gray shim rods has been determined to be 1% $\Delta k/k$ each as predicted in design, although values for individual rods may range from 0.3% to 1.5%.

- The average black shim rod worth is approximately 1.5% $\Delta k/k$, as compared with the design prediction of 3.6%. This low value will introduce some problems in operation.

- The excess reactivity for a core loaded with 49 fuel elements and 31 aluminum filler pieces in the nine core experimental facilities was measured to be 1.5% as compared with the design prediction of 11%. The primary reason for the low value of excess reactivity appears to be high boron content which, because of metallurgical and analytical uncertainties, ran over the

specification value in the first 180 fuel elements fabricated. Steps are being taken to bring the boron into line on the next lot. It may also prove desirable to increase the fuel content.

Control Rods and Drives

Three major problems were encountered in preoperational tests of the ETR control rods and drives. Two of them have been solved and the third will require a redesign of the fuel section (*1*) in the control rods. The problems are as follows:

1. A pressure drop of 65–75 psi is required to give the design coolant velocity of 35 psi through the fuel section of the control rods. This is roughly 50% higher than the calculated value of 45 psi. The discrepancy is accounted for by a design computational error. The net result is that the flow through the fuel section of the control rods as presently designed will provide insufficient cooling for full power operation at 175 Mw. Under the core ΔP required to give 18 ft/sec through the fuel elements, the coolant flow through the fuel section of the control rods will be adequate to permit a maximum reactor power of 90 Mw.

So far as the heat-transfer problem is concerned, the most likely possibility for remedial action appears to be a simplification of the latching system that will allow the insertion of two or three additional fuel plates without increasing the pressure drop over the present value. This will reduce the fuel content per plate and hence reduce the heat flux to the point where the plates can be cooled by a flow of about 30 ft/sec under 175-Mw operation. This flow will require a ΔP of 40–45 psi.

2. The carbon-steel actuator rod in the control-rod drive mechanism was found to corrode to such an extent that the rod drive would not scram after a week of intermittent operation. This has been remedied by changing the material of construction to 17-4 PH stainless and increasing the clearance between the rod and the guide bushings.

3. The drive-rod magnets were found to provide inadequate force to hold the control rods after the mechanism had been operated for a short time. The magnet amplifiers are designed to give 100 ma in the coil windings during normal operation, but after the rods had been operated for some time, the current required to hold them went up to 300 ma. Calculations indicated that the pole pieces were magnetically saturated under the operating conditions. As a remedial measure, the pole pieces were cut back to provide greater holding area and the magnets now operate satisfactorily on about 125 ma.

Primary Coolant System

Unlike the MTR, which is cooled by a stream of water from an overhead reservoir, the ETR derives its cooling from a pump-driven water stream. The most important difference between the two is in the type of emergency coolant protection provided in the event of power failure, particularly during the first few minutes after shutdown when the fission heat is a relatively high fraction of the full power heat. In the MTR, the ever-present overhead reservoir of about 150,000 gal is sufficient to provide the full coolant flow of 20,000 gpm for a period of 7.5 min, if needed, after a power failure stops the pumps and scrams the reactor. In case of power failure at the ETR the inertia of the primary coolant pumps and water stream have been calculated by the designer to allow the reactor to be shut down safely to the point where thermal circulation will suffice to remove the after heat. As additional protection, we have installed a failure-free power source and connected the emergency coolant pumps to it.

Since the scram time for the differential pressure recorder is over 1 sec it seems best to add at least two fast-response differential-pressure scrams before taking the reactor to high-power operation. This will be done. There must be at least two avenues by which the reactor can be scrammed in 500 millisec or less in the event of a commercial power failure.

In addition, it has been found that the control range designed into the system cannot accommodate the large pressure drop required to operate at low core velocities. Since the reactor is to be operated initially at reduced flows, it has been necessary to install orifices in the primary coolant lines to restrict the flow to a safe value for the fuel elements now in use.

With the foregoing exceptions, the primary coolant system characteristics including pressure transient response and heat exchanger performance appear to be satisfactory.

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Cockcroft-Waltons—Good Neutron Producers

Increasing use of the *d-t* reaction to produce 14-Mev neutrons and the *d-d* reaction for 2.9-Mev neutrons is bringing new fame to a work horse among accelerators, the Cockcroft-Walton or cascade-rectifier type. In its operation electrons are "pumped" up through succeeding stages to the top of the cascade where their potential energy is roughly the product of the peak input potential by the number of stages.

Strong points of the cascade-rectifier design are simplicity (no moving parts) and relatively high beam currents. This is just fine for research applications, and at least one manufacturer recommends them for processing.

The accelerator unit is not complete until one has coupled an ion source and an accelerating tube to the high-potential supply. Since the ion source must be at a high potential relative to ground, there is a problem of supplying it with heating power and connecting it to remote control knobs.

Three manufacturers are now offering Cockcroft-Waltons to the American market. They are American Instrument Co., Silver Spring, Md.; Applied Radiation Corp., Walnut Creek, Calif.; and Philips Electronics, Mt. Vernon, N. Y. A table of the characteristics of the accelerators that they build is on this page. In the sections that follow are brief descriptions of these devices.

ARCO Generator Makes Neutrons in Arkansas

First of the Applied Radiation Corp.'s Cockcroft-Waltons (see Fig. 1) is a 350,000-volt, 1,000-μa installation that will accelerate positive ions for the chemistry department of the University of Arkansas. Richard Fink will use it to make up to 10^{11} 14-Mev neutrons per second by hurling deuterons at a tritium-soaked zirconium target. He has already produced 2×10^{10} *d-d* neutrons. He can produce a 1.8-ma deuteron beam at 380 kv and focus it into a spot that is 1.2 mm in diameter.

Eventually Fink hopes to increase the output many times by increasing the output potential to 500,000 volts

Characteristics of Cockcroft-Walton Generators

	Philips					*American Instrument*		*ARCO*
No. of stages	2	3	4	4	7	4	13	10
Max voltage (kv)	350	525	700	1,000	1,750	250	500	400
Max beam current (ma)								
accelerator	8	8	8	4	4	5	5	3
ion source	1–1.2	1–1.2	1–1.2	1–1.2	—	—	—	—
at target	1	1	1	1	0.8	1	1	1.5
Max beam power (watts)						250	500	400
Primary frequency (cps)	500	500	500	500	500	400	54,000	1,000
Input power (kw)	30	30	30	60	60	4	4	6
Ripple (%, peak to peak, at max voltage)								
filter	0.04	0.05	0.06	—		0.1	0.1	0.1
no filter	0.4	0.5	0.6	0.3	0.5	<1.0	<1.0	2.0
Price ($ 10^3)	48.1*	52.3*	55*	130*	—	80†	150†	79‡
Pressurized or oil immersed	non-press	non-press	non-press	press	press	oil	oil	non-press

* FOB Mt. Vernon, N. Y., without duties. † FOB Silver Spring, Md., including installation. ‡ FOB Walnut Creek, Cal., including supervision of installation.

FIG. 1. Applied Radiation Corp. recently installed this accelerator at University of Arkansas

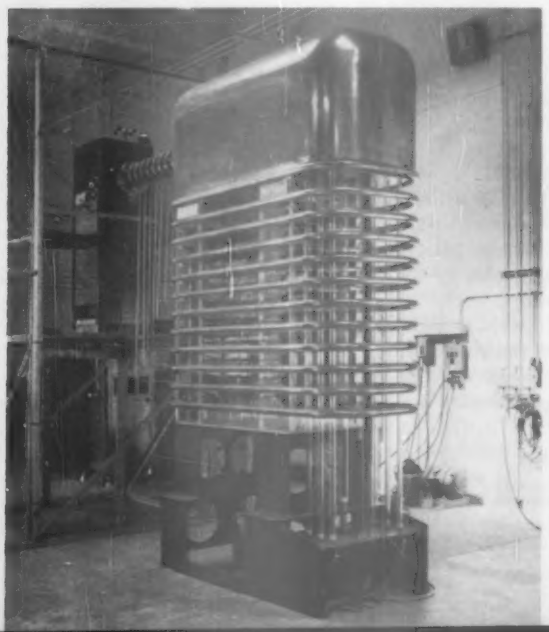
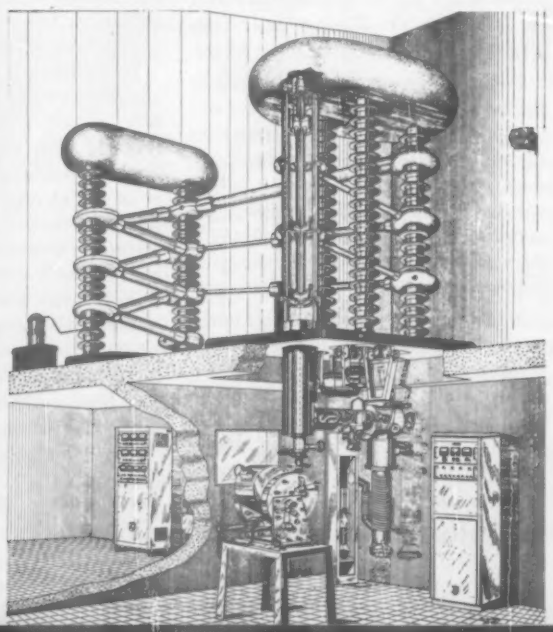
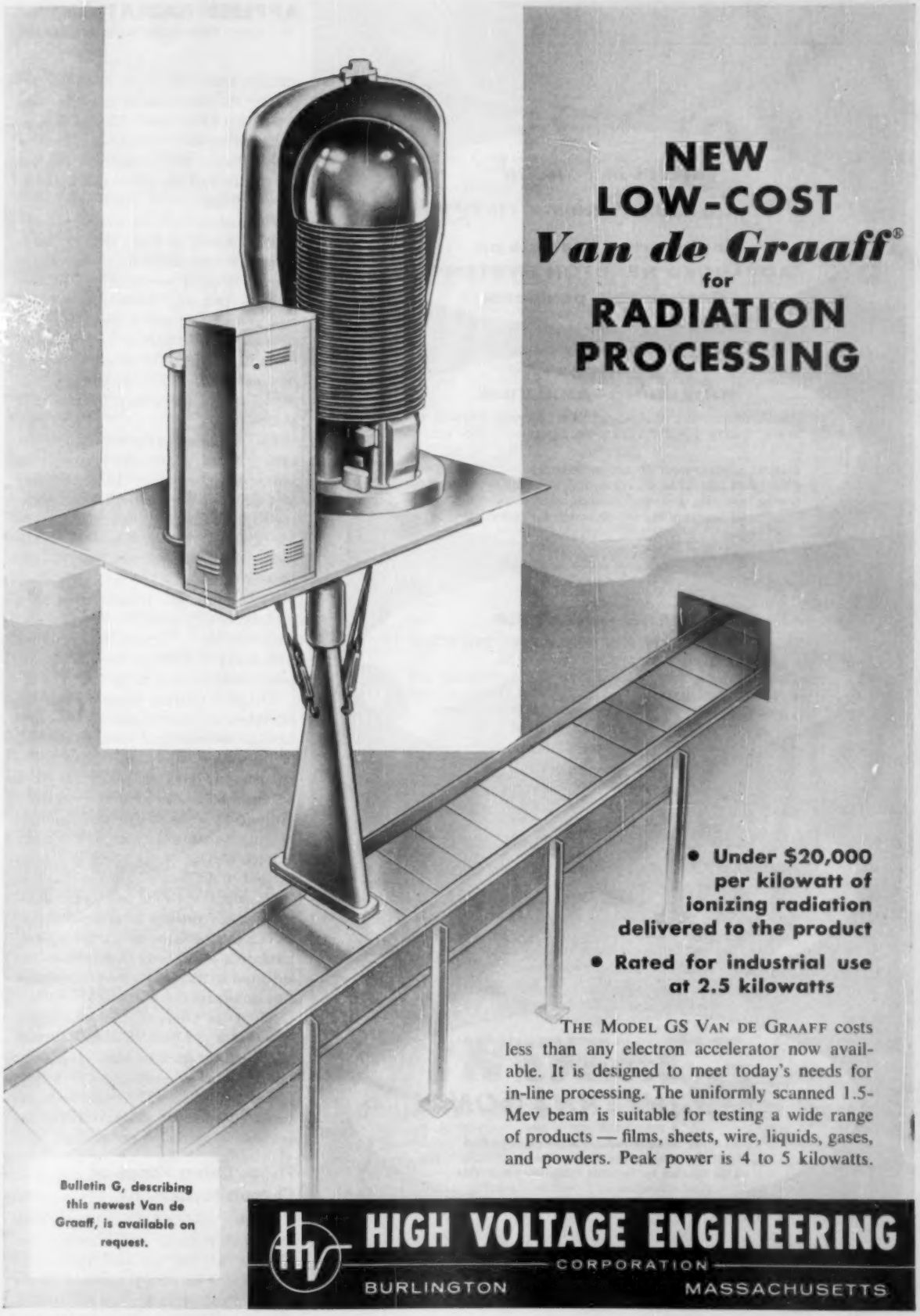


FIG. 2. Philips Electronics uses oval corona shields. Insulating columns house belts and rod drives





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This article starts on page 106

and the beam current to 3 ma and replacing the zirconium target with a regenerating silver one. The plan is to bombard the silver with both deuterons and tritons. The beam will replace the tritium and deuterium consumed in the reactions.

The cold-cathode ion source will operate hundreds of hours either continuously or intermittently at full beam current without servicing. It can accelerate protons, deuterons, tritium ions and alphas, and it should be possible to produce heavier ions with significant yields. To avoid problems inherent in belt drives, all power is conveyed to the ion source by insulated shafts.

The Arkansas power supply is operated without a pressure enclosure at atmospheric pressure. Larger accelerator dimensions are required, but housing requirements are about the same as for pressurized devices in view of the room required for removal of the pressure shell.

The installation is considered as a prototype; others will be designed and built to order. Designs are available with beam energies of 200–750 kv and total beam currents to 10 ma.

ARCO is offering direct-current accelerators in two categories. The first has the conventional cascade rectifier power supply described above. The second, for greater potentials is a device that stacks several Cockcroft-Waltons in series to get higher output potentials than are otherwise available.

Each section of the stack is a pressurized, unfiltered cascade rectifier in itself, supplied by its own permanent-magnet generator. All generators are driven by the same motor through an insulating shaft, and their phases are adjusted so that the ripple is reduced to a minimum.

ARCO is prepared to build generators with 3-Mv and 5-ma outputs. They can be used to accelerate either positive ions or electrons. It is predicted that they will be useful for research purposes and competitive for commercial radiation processing.

Philips Offers Range of Outputs to 1,750 Kv

Three models of nonpressurized Cockcroft-Waltons with output potentials to 700 kv and pressurized models with outputs of 1.0 and 1.75 Mv are available from Philips Electronics.

The nonpressurized accelerators (see Fig. 2) have two high-potential stacks, one for the cascade-rectifier unit and the other for the accelerating tube and a ripple-smoothing filter. In some installations a third stack is used for further filtration between the other two.

Selenium rectifiers rated at 10 ma and 200-kv peak inverse potential supply the rectification. An r-f ion source is mounted in the corona shield on top of the accelerating-tube section. Three insulating columns supporting this shield enclose, respectively, the control rods for the ion source, the driving belt for its power generator, and the smoothing filter.

Two separate stabilizing systems hold the over-all stability of the accelerating potential to 1 part in 1,000. For slow fluctuations a reference voltage is tapped from a resistance-capacitance divider and compared with a stabilized low-potential supply. The error signal is amplified and fed back to control the field of the 500-cps generator that serves as a primary exciter. Fast fluctuations are suppressed by an electronic regulator standing between the cascade generator and ground.

In pressurized models the accelerating tube is on the central axis of the tank and three supporting tubes are placed symmetrically around it. The motor that drives the generator for the r-f ion source is enclosed in the pressure tank.

American Instrument Uses Oil-Immersed Power Supply

Unusual compactness and flexibility are available in the oil-immersed cascade power supplies and caster-mounted ion source and accelerating tube produced as a unit by the American Instrument Co.

Four AMINCO 250-kv units are currently in use at the following laboratories: U. S. Naval Research Laboratory, Los Alamos, Oak Ridge, and Argonne National Laboratories.

The high-potential terminal is connected to a cabinet that houses the ion source and associated electrical equipment. In the 250-kv unit four tubular insulating columns support the ion-source cabinet on a caster-mounted base. Through one of the columns runs the belt that powers the ion source. Manual control of the ion

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OUTPUT CURRENT	0 to 1 ma	0 to 1 ma	0 to 1 ma	0 to 5 ma at 500 to 1500 volts; 0 to 2 ma at 1500 to 2000 volts	0 to 15 ma DC	0 to 1 ma
OUTPUT POLARITY	pos. or neg.	pos. or neg.	pos. or neg.	pos. or neg.	pos. or neg.	pos. or neg.
REGULATION VS. LINE	.03% max. from 100 to 130 volts	.03% max. from 100 to 130 volts	.01% max. from 100 to 130 volts	.01% max. from 100 to 130 volts	.01% max. for 20% line change	.01% max. from 100 to 130 volts
REGULATION VS. LOAD	.03% no load to full load	.03% no load to full load	.01% max. no load to full load	.03% no load to full load	.01% max. for 2 ma change	.01% max. no load to full load
STABILITY	.02% per hour	.01% per hour	.005% per hour	.005% per hour	.005% per hour	.005% per hour
RESOLUTION	100 mv at any output voltage	100 mv at any output voltage	100 mv at any output voltage	100 mv at any output voltage	10 mv at any output voltage	100 mv at any output voltage
CALIBRATION ACCURACY	2%	1%	Better than 1%	Better than 1%	Better than .5%	1%
RIPPLE	5 mv max.	5 mv max.	Less than 5 mv RMS	Less than 5 mv RMS	Less than 5 mv RMS	5 mv max.
SIZE AND WEIGHT	19"W x 7"H x 13"D—22 lbs.	19"W x 7"H x 13"D—22 lbs.	19"W Rack x 7"H x 13"D	19"W Rack x 7"H x 13"D—27 lbs.	19"W x 10½"H x 14"D—46 lbs.	19"W x 10½"H x 14"D—42 lbs.
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source is provided through 26-in.-long Lucite rods.

The ion-source is shown in Fig. 3. Ions for the beam are formed in a chamber that contains hydrogen and deuterium at 1.5×10^{-3} mm of Hg. A 300-ma arc is maintained between a filament and the open end of this chamber, and ion-making electrons from the arc and filament are caused to spiral down the chamber axis by a solenoid field. Positive ions that drift out of the chamber are drawn into the

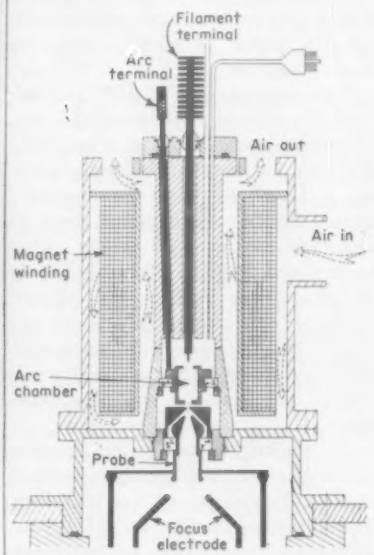

FIG. 3. In American Instrument's ion source electrons ionize deuterium-hydrogen mixture

accelerating tube by a negative voltage on a probe. This injection voltage can be controlled between 0 and 10 kv and is used to help focus the beam. Beams of up to 250 μa can be focused to less than 1-mm diameter or spread uniformly over a circle of up to 6-mm diameter.

The accelerating tube consists of Pyrex-insulated aluminum electrodes cemented together. Textolite rods hold the column in compression, and Monel corona rings connected by resistors and protective spark gaps maintain a uniform potential gradient and prevent breakdowns within the tube. Flapper valves and roughing valves make it simple to break the vacuum in the target section, the accelerating section, or both without shutting down the vacuum system.

BOOKS

Radiation Shielding

By B. T. PRICE, C. C. HORTON and K. T. SPINNEY (Pergamon Press, London, 1957, ix + 350 pages, $10.00).

Reviewed by K. H. PUECHL, Manager, Theoretical Department, Walter Kidde Nuclear Laboratories, Inc., Garden City, N. Y.

Considered as a review article, this book is a most valuable publication. The content is broader in scope than for any other book yet written on shielding and the detailed bibliography is quite complete. Where the "Reactor Shielding Design Manual" (NU, Oct. '56, p. 90) deals only with reactor shielding, Price et al. also cover in some detail shielding of accelerators and radioisotopes. In particular, the section on electron and secondary bremsstrahlung shielding is more complete than discussions found elsewhere.

An individual well versed in general nuclear theory will find "Radiation Shielding" a convenient starting point for specializing in shield design. An engineer, however, will derive much less from one reading since some familiarity with such topics as neutron slowing-down theory, wave-particle duality, electron-shell structure, essentials of nuclear structure and radiation-detection instrumentation is assumed. Actually the references to these topics are such that a reader familiar with the subject of radiation shielding realizes that lack of knowledge in these fields is no great limitation for the initial understanding of shielding phenomena. However, for a less informed reader such references may introduce a handicap. Minor reorganization of the presentation of topics could have avoided this difficulty.

By itself, "Radiation Shielding" does not seem suitable as a college text for advanced undergraduate or graduate students. Elementary theories such as radioactive buildup and decay and neutron-diffusion theory are described in detail, while more elaborate theoretical procedures such as age theory, transport theory, and the polynomial method for attaining solutions to the transport equation are described all too briefly. A happier medium would seem to lie between these two extremes. The wide brush technique applied to the more advanced theoretical procedures is acceptable only because of the specific references that are given.

As a shielding handbook, this volume is useful in that many formulae and graphs of both theoretical and experimental results are presented. Since one cannot expect all data to be included in any one volume, for this purpose the book seems to be a worthwhile complement to the "Reactor Shielding Design Manual."

The last chapter is a down-to-earth chronological description of how a reactor shield design is evolved. The presentation is good; however, the explanation is given by constant referral to equations in other chapters. A better approach would have been to repeat the equations and also carry through a shield design working with a particular reactor.

While presenting much information in readily usable form, little original work seems to have gone into the preparation of this book. An example occurs in the description of buildup factors for gamma-ray attenuation. Tables and curves are given for plane monodirectional source buildup factors and point isotropic source buildup factors, as obtained by the moments method. Curves are also given of Peebles' buildup factors for slant penetrations as obtained by the method of successive scatterings. No attempt has been made to obtain correlation between these two methods. Certainly, a few simple integrations could have yielded a comparison.

Any book covering such a broad scope can be expected to suffer from a number of omissions. In the discussion of neutron-attenuation procedures, diffusion theory, age theory, and removal-cross-section theory are presented. It would seem that multigroup methods should also have been considered. Another omission occurs in the discussion of radiation leakage from the reactor core. Probably the most accurate procedure, that suggested by Feynman and commonly used for calculating neutron leakage from a fuel element in estimating the fast fission factor, is completely ignored. While the discussion of relative biological effectiveness may be suitable for reactor shielding, for a book that is intended to cover the broad field of radiation shielding, the discussion seems totally inadequate.

These omissions are counterbalanced to a considerable extent by the interesting information that is not generally

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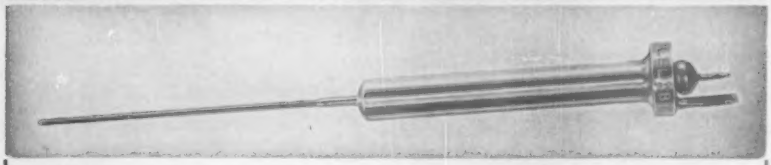

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included in shielding discussions. This includes such items as the probability of backscattering of electrons incident upon various surfaces, the fraction of electron energy released as bremsstrahlung and the fluorescent yield of materials irradiated by gamma rays.

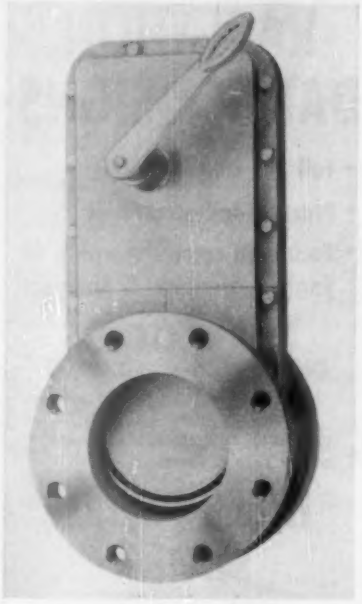
The authors write in a clear, unstilted style that tends to sustain interest. After reading mostly technical reports on shielding, one is pleasantly surprised to find that the over-all subject is amenable to such treatment.

ALSO OF NOTE

Logistic and Economic Feasibility Study on Radiation Sterilization of Foods (PB 121961). This study was made by North American Aviation for the Quartermaster Food and Container Institute for the Armed Forces. Various gamma sources, X-rays and accelerators are considered. It is concluded that electron accelerators are likely to be used for large-capacity plants requiring high radiation exposures, while gamma sources have an economic advantage for low-exposure processes. 107 p. *Office of Technical Services, U. S. Department of Commerce, Washington 25, D. C., $3.25.*

AEC biology and medicine reports: **The distribution of plutonium in the soils of central and northeastern New Mexico as a result of the atomic bomb test of July 16, 1945,** (UCLA—406, Sept. '57, 23 p., 75¢); **Biology and medicine quarterly report, April, May, June, 1957, Radiation Laboratory, U. of Calif.** (UCRL—3880, 33 p., $1).

AEC metallurgy and ceramics reports: **Growth rates and microstructural characteristics of 300° C rolled uranium rods on thermal cycling** (ANL—4956, May '56, 22 p., 75¢); **Effects of high burnup on natural uranium** (ANL—5539, May '57, 45 p., $1.25); **Investigation of methods for end capping stainless steel pins** (BMI—1090, May '56, 39 p., $1); **Bubble stirring in a low temperature model of a fused salt electrolysis cell** (KAPL—1762, July '57, 23 p., 75¢); **The fast oxide breeder—fuel irradiation experiments** (KAPL—1784, Aug. '57, 20 p., 50¢). *Office of Technical Services, U. S. Department of Commerce, Washington 25, D. C.*



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Six-inch high-vacuum valve (above) features a choice of flange dimensions and minimum space between flange faces. Valve, model VG-106T, is quick acting, has straight-through opening.—Vacuum Research Co., 420 Market St., San Francisco 11, Calif.

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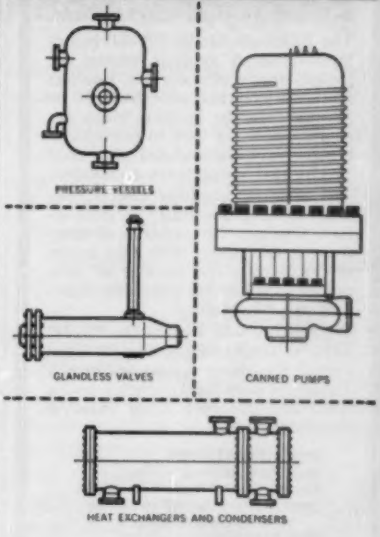

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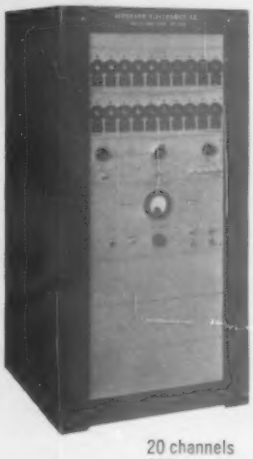

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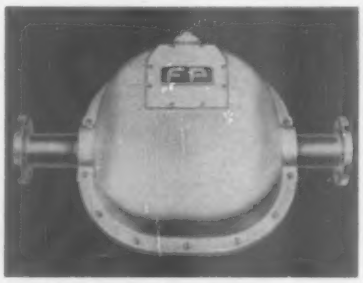

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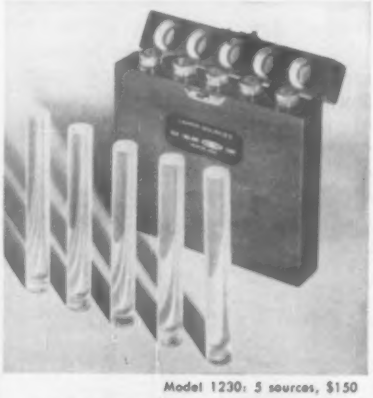

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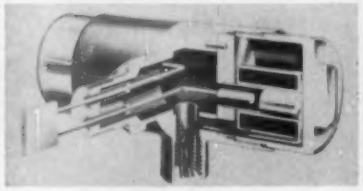

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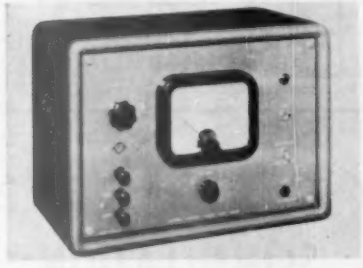

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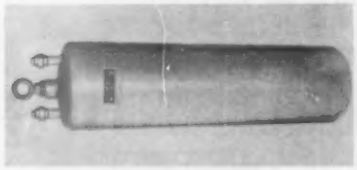

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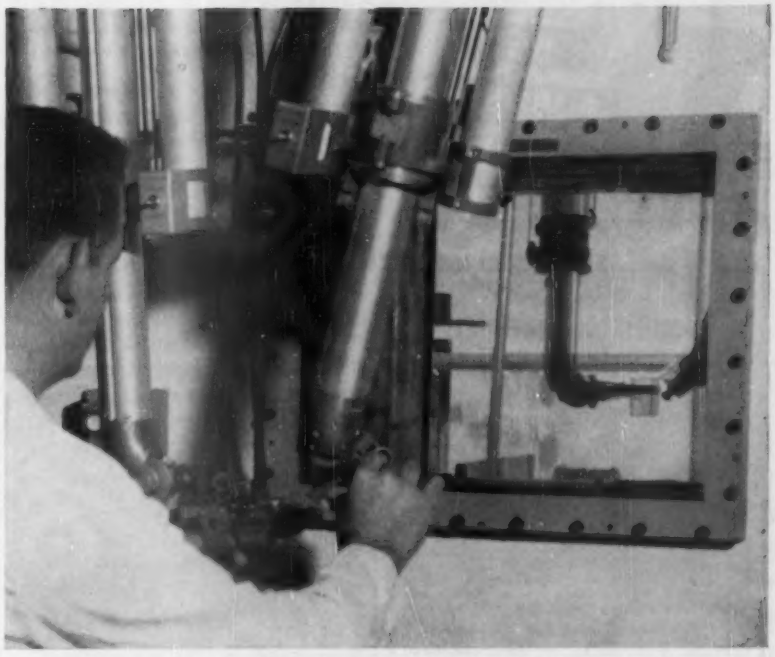

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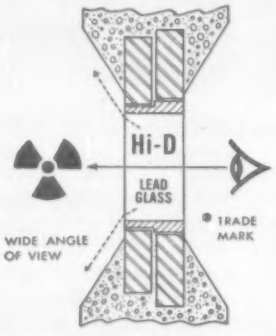

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is >100 meg. This switch requires <40 watts of single-phase, 400-cycle (60-cycle available on special order), 115-v, a-c power.—Instrument Development Laboratories, Inc., 67 Mechanic St., Attleboro, Mass.

• New high-speed sampling switch has 40 individually replaceable contacts. The switch can be supplied in multideck configurations with various numbers of contacts per deck and with various motor speeds and voltages. Specifications include: dynamic contact resistance <0.25 ohms; open circuit resistance >1,000,000 meg; minimum switch cycle time, including breakaway, transit, and dwell times <500 μsec; contact make-or-break current up to 10 ma; signal levels up to 10 v.—The Magnavox Co., 2255 Carmelina Ave., Los Angeles 64, Calif.

D-C Overpotential Tester

The Model 3050-5 is the latest addition to a series of overpotential testers. This unit features qualitative and quantitative nondestructive dielectric testing and "burn" currents for positive fault identification. It has an output range of 0–50 kv at 0–5 ma; 0–5, –20 and –50 kv voltmeter ranges; 0–50, –200, –500, –2,000 and –5,000 microamperemeter ranges; 105–125 v, 50–60 cycle, single-phase input; reversible polarity and 2% ripple at full resistive load.—Beta Electric Div., Sorenson & Co., Inc., 333 E. 103 St., New York 29, N. Y.

250-kv Supply

Model 4250 is an air-insulated selenium-rectified 250-kv, 2-ma power supply. Unit has input voltage of 105–125 volts, with ~2.5% ripple at rated power output, and internal impedance of 11 megohms.—Beta Electric Division, Sorenson & Co., Inc., 333 East 103 St., New York 29, N. Y.

Electronic Rack Cooler

Model 1H300 rack mounted centrifugal blower delivers 100 cfm. Accompanying this unit is a series of matching filter grill assemblies.—McLean Engineering Laboratories, PO Box 2208, Princeton, N. J.

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PRODUCTS & MATERIALS

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LITERATURE AVAILABLE

Fast pulse transmission equipment. 5 p.—Electrical & Physical Instrument Corp., 42–19 27 St., Long Island City 1, N. Y.

Particle accelerators Bulletin H. shows Van de Graaff particle accelerators for research and industry.—High Voltage Engineering Corp., Burlington, Mass.

Twenty new instruments that have been added to line of digital and analog instrumentation are noted in catalog C-704.—Berkeley Division, Beckman Instruments, Inc., 2200 Wright Ave., Richmond, Calif.

Nuclear laboratory equipment—counting, sample preparation, personnel protection and survey—featured in bulletin SN. 28 p.—Tracerlab, Inc., 1601 Trapelo Rd., Waltham 54, Mass.

High-voltage-supply unit, model 212, discussed in data sheet.—Radiation Instrument Development Laboratory, 5737 S. Halsted St., Chicago 21, Ill.

Potentiometers' mechanical and electrical specifications are presented on rotating wheel display card.—DeJur-Amsco Corp., 45–01 Northern Blvd., Long Island City 1, N. Y.

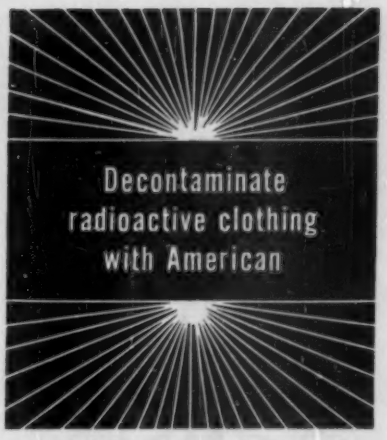
Membership roster and product directory with listing of more than 250 western states electronic firms.—West Coast Electronic Mfrs. Assn., 342 N. LaBrea, Los Angeles 36, Calif.

Moisture monitor, type 26–301, for monitoring or control of trace quantities of moisture in gases or gaseous mixtures, described in bulletin 1834A.—Consolidated Electrodynamics Corp., 300 N. Sierra Madre Villa, Pasadena, Calif.

Pumps, sealless plastic and stainless steel pumps, in catalog 10.0.—Vanton Pump & Equipment Corp., 201 Sweetland Ave., Hillside, N. J.

Ceramic research and description of firm's activities in this field. 20 p.—Gladding McBean & Co., 2901 Los Feliz Blvd., Los Angeles 39, Calif.

Liquid level and flow controls used in EBWR are described in 10-p booklet.—Magnetrol, Inc., 2110 S. Marshall Blvd., Chicago 23, Ill.



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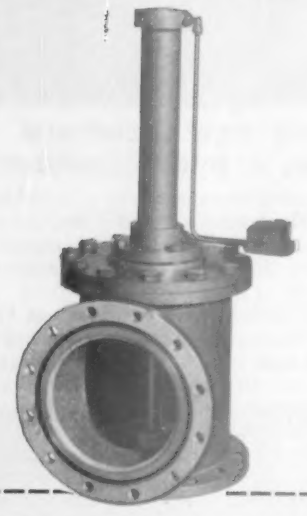

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Transistor test equipment listed on catalog sheet 101.—Electronic Research Associates, Inc., 67 E. Centre St., Nutley, N. J.

"Tech-Talk," a new technical newsletter discusses developments in specialized instrumentation.—Schlumberger Well Surveying Co., Ridgefield, Conn.

Laboratory monitor model LM 48 discussed in catalog sheet.—Radiation Instrument Development Laboratory, 5737 S. Halsted St., Chicago 21, Ill.

Magnesium-thorium alloys, an evaluation of their properties and characteristics. 12 p.—Brooks & Perkins, Inc., 1950 W. Fort St., Detroit 16, Michigan.

Voltage regulators and their application to 12 different industrial problems in bulletin 5.00.2. 28 p.—Electric Regulator Corp., Pearl St., Norwalk, Conn.

Piping hangers and supports, with technical information and specifications in bulletin 551. 56 p.—Bergen Pipesupport Corp., 50 Church St., New York 7, N. Y.

INDUSTRY NOTES

▶**20th Century Electronics** has moved to King Henry's Drive, New Addington, Surrey, England.

▶**Tracerlab, Inc.** has appointed George T. O'Dea controller.

▶**Allis-Chalmers Mfg. Co.** has formed Allis-Chalmers International as a major operating division. The new division will be responsible for all manufacturing, engineering and sales outside of the U. S. and Canada. P. F. Bauer, formerly general manager, industrial equipment division, was named managing director.

▶**Single Crystal Corp. of America,** Saxonburg, Pa., has been formed and will grow single crystals, many with nuclear applications.

▶Ralph E. White, previously with Millrich Engineering Corp., has joined **Riggs Nucleonics Co.,** Altadena, Calif., as vice-president and director of research and engineering.

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NUCLEAR CALENDAR

Jan. 27–28—Sixth Scintillation Counter Symposium, AEC, AIEE, IRE and NBS, Washington, D. C. (*Shoreham*). Four half-day sessions at biennial symposium will cover these sessions: phosphor and Cerenkov scintillators; photomultipliers; energy and time resolution; scintillation counter applications. Films showing latest low-level counting techniques will be shown evening of 27th. Contact G. A. Morton, RCA Laboratories, Princeton, N. J.

March 3–6—American Society of Mechanical Engineers' gas turbine power division conference and exhibit, Washington, D. C. (*Shoreham*). Contact L. S. Dennegar, ASME, 29 West 39 St., New York 18.

March 10–21—Special two-week course in veterinary radiological health, AEC and ORINS, at Oak Ridge. Contact Maj. Max Nold, U. S. Air Force Veterinary Corps, ORINS, P.O. Box 117, Oak Ridge, Tenn.

March 17–21—Nuclear Congress will include four events, at International Amphitheater, Chicago: **A.** Fourth Nuclear Engineering & Science Congress (EJC), running all five days. Contact congress manager, American Institute of Chemical Engineers, 25 West 45 St., New York 18. **B.** Atomic Industrial Forum Atom Fair, all five days, contact J. V. Friel, 304 Architects Bldg, Philadelphia 4. **C.** Sixth Hot Laboratories & Equipment Conference, 19–20th; contact Frank Ring, Jr., ORNL, Oak Ridge, Tenn. **D.** Sixth Atomic Energy in Industry Conference, National Industrial Conference Board, 17–19th; contact John J. McMahon, 460 Park Ave., NYC.

March 24–27—National Convention IRE, New York (*Waldorf, Coliseum*). 275 papers in 55 sessions. Contact E. K. Gannett, IRE, 1 E. 79 St., New York 21.

March 26–28—20th meeting, American Power Conference, Chicago (*Sherman*). Contact R. A. Budenholzer, Illinois Institute of Technology, 3300 Federal St., Chicago 16.

March 31–April 2—Conference on utilization of atomic energy, Texas A. & M. College, College Station, Tex. Will cover reactors, isotopes, waste disposal, petroleum applications, education. Contact R. E. Wainerdi, Texas A. & M., College Station.

April 20–23—Canadian–U. S. chemical engineering conference, American Institute of Chemical Engineers and Chemical Institute of Canada, Montreal. Contact H. R. L. Streight, DuPont Co. of Canada, PO Box 660, Montreal, Quebec, Canada.

May 27–29—Third annual reactive metals conference, American Institute of Mining, Metallurgical and Petroleum Engineers, Buffalo (*Statler*). Contact S. F. Urban, National Lead Co., Buffalo, N.Y.

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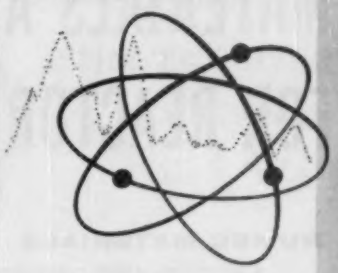

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NEWSMAKERS

Leonard J. Koch fills the newly-created post of deputy director, Reactor Engineering division, at Argonne National Laboratory. Formerly associate director of the division, Koch, 37, has worked at Argonne for almost ten years. He was associate project engineer for EBR-1, and is now project manager for EBR-2, a post he will continue to hold.

Vitro International, a new operating company with headquarters in Switzerland, has been set up by Vitro Corp. of America to represent all Vitro operations overseas. **Norman A. Spector,** vice-president of Vitro Corp., retires from that post to become president of Vitro International. **Ralph L. Brown,** former assistant sales manager of Vitro Engineering Co., will be vice-president of the overseas company based in Switzerland. The new unit is Vitro's ninth operating division.

Edward R. Trapnell of the nuclear energy division at Bozell & Jacobs has taken a leave of absence to join the staff of the International Atomic Energy Agency, and has already left for Vienna. He will work under Director-General W. Sterling Cole on the Agency's public information program. Trapnell has been an atomic energy public information specialist since his Manhattan District service.

Phillips Petroleum Co.'s atomic energy division has added physicists **James Cline** from the Univ. of Michigan and **Park French** from Case Institute; reactor engineer **Don L. Olson** from the Univ. of Utah; and health physicists **Gile M. Mitchell** from Western Montana College of Education and **Richard L. Van Tuinen** from the Univ. of Oregon.

Leonard E. Link of Argonne, associate chemical engineering in the Reactor Engineering division, has spent a month in Turkey to advise the Turkish government on its nuclear planning, including specifications and site selection for Turkey's first research reactor.

Kentucky set up the post of director of the new Nuclear Information division

in the State's Department of Economic Development, and named to it **Robert H. Solomons III,** a former newspaperman more recently information officer at AEC's Oak Ridge Operations Office. Solomons has been associated with the atomic energy program for six years.

C. A. Benz is head of Peter F. Loftus Corp.'s new Nuclear Engineering department.

Atomics Associates Inc. has added **Theodore Voutselas** and **William L. Waits** to its staff.

Theo K. Bierlein and **Bernard Mastel,** General Electric metallurgists at the Hanford atomic works, were named joint winners of the $500 F. F. Lucas award for their electron micrographs of zircaloy-2.

Martin Goland, vice-president of Southwest Research Institute, San Antonio, Texas, has taken on the additional duties of director of the Institute.

T. G. Pickavance has been chosen to be first director of Britain's Rutherford High Energy Laboratory, being built adjacent to Harwell by the National Institute for Research in Nuclear Science.

Olin Mathieson Chemical Corp. has named **S. J. Wommack** assistant general manager of the Nuclear Fuel division, to direct the production, technical and quality control departments. With Olin since 1950, Wommack has been general manager of the chemical and industrial manufacturing division of the Olin Mathieson International Corp.

Denton Massey, general manager of AMF Atomics (Canada) Ltd. since 1956, has been elected a vice-president and director, and continues as general manager; **Roy B. Snapp,** divisional vice-president of AMF Atomics, and **B. V. Elliot,** general counsel of the company, also were elected directors.

Hans Eduard Band, formerly with MIT's Lincoln Laboratory, General Electric, and Melpar Inc., has been named to the research staff of Technical Operations Inc.'s laboratory headquarters at Burlington, Mass.

Tracerlab Inc. has named **Robert S. Schmidt** district sales manager for nine Western states, Alaska and Hawaii, with headquarters in Richmond, Calif.

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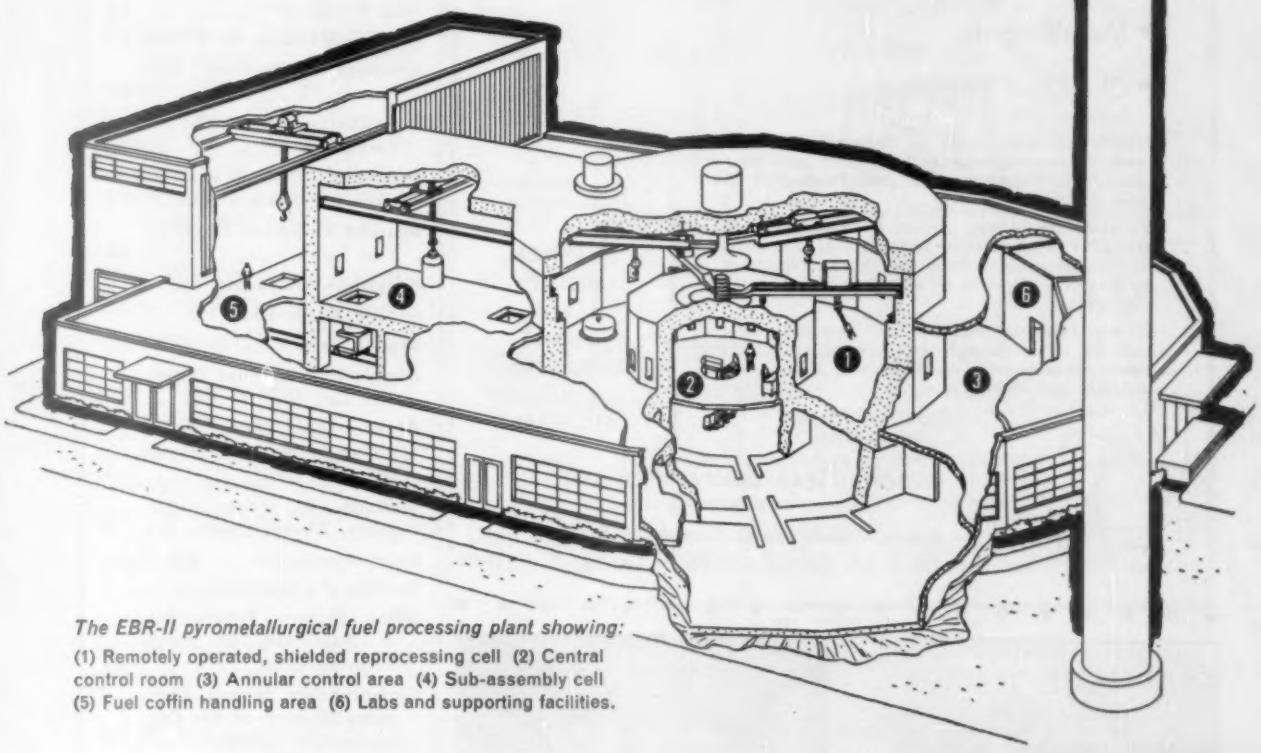

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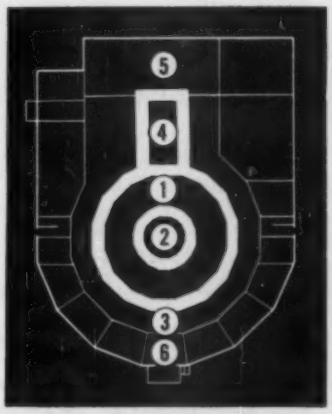

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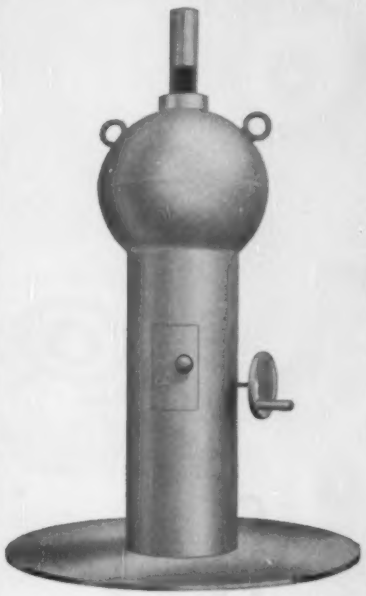

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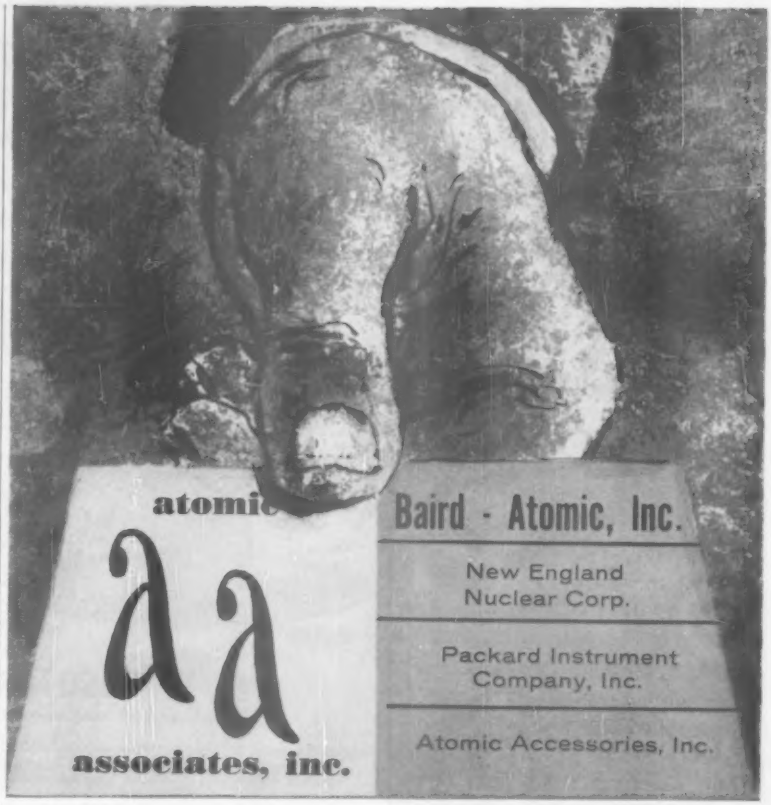

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